AD-A151 895 A DECISION SUPPORT METHODOLOGY FOR SPACE TECHNOLOGY ADVOCACY(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING P H RENSEMA ET AL. DEC 84 1/4

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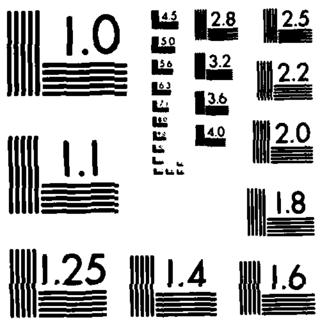

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A DECISION SUPPORT METHODOLOGY

FOR SPACE TECHNOLOGY ADVOCACY

THESIS

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AFIT/GSO/OS/84D-3

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS: None
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFIT/GSO/OS/84D-3	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: School of Engineering, Air Force Institute of Technology; 6b. OFFICE SYMBOL (If applicable): AFIT/EN	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code): Wright-Patterson AFB, Ohio 45433	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT NO.
11. TITLE (Include Security Classification): "See Box 19"	

12. PERSONAL AUTHOR(S): Rensema, Peter Howard & Chapman, Randall William

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
MS Thesis	FROM ____ TO ____	1984 December	378

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	DECISION MAKING; OPERATIONS RESEARCH; RESEARCH MANAGEMENT; MILITARY RESEARCH; TECHNOLOGY FORECASTING; SPACE TECHNOLOGY; ANALYTIC HIERARCHY PROCESS; DECISION SUPPORT; DOCTRINE
12	02		
05	10		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Title: A DECISION SUPPORT METHODOLOGY FOR SPACE TECHNOLOGY ADVOCACY

Advisor: Lt Col Mark Mekaru
Coadvisor: Maj Ken Feldman

Approved for public release: IAW AFR 190-17.
Lynn E. Wolaver 21 Feb 85
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Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB OH 45433

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL: Lt Col Mark Mekaru, PhD; Maj Kenneth Feldman, PhD	22b. TELEPHONE NUMBER (Include Area Code): 513-255-3362; 22c. OFFICE SYMBOL: AFIT/ENS

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

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AFIT/GSO/OS/84D-~~8~~

A DECISION SUPPORT METHODOLOGY
FOR SPACE TECHNOLOGY ADVOCACY

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Space Operations

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Major, USAF

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Captain, USAF

December 1984

Approved for public release; distribution unlimited

Preface

The purpose of this study was to develop a decision support methodology for space technology advocacy. Previous investigations and our own research indicated that traditional quantitative decision models inadequately modeled the space R&D portfolio selection process.

This report is limited in scope to an analysis of the R&D environment and a description of the proposed decision support methodology. The results of testing the validity and suitability of the methodology are also included in the report. The methodology could be easily transformed into a decision support system.

We would like to thank our advisors, LtCol Mark M. Mekaru and Maj Ken Feldman of the Air Force Institute of Technology, who gave timely guidance essential to the completion of this study. We would also like to thank the Air Force Space Technology Center and especially Col Ben Bolton, LtCol Dave Lange, Maj John Ditucci, and Mr. Tim Spinney for their sponsorship and advice in this effort. We are especially grateful to LtCol Pete Soliz of the Space Technology Center for his unlimited support and patience in assisting us with our research project. We are also appreciative of Mr. George Husman and Mr. Dave Massey of the Air Force Wright Aeronautical Laboratories for their participation in this project. Without the assistance of all these people this research effort would not have been possible.

Finally, we wish to acknowledge the patience, understanding and support we received from our wives, Dawn and Martha. Without them none of this would exist.

Pete Rensema

Randy Chapman

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Abstract

A decision support methodology for space technology advocacy was developed in lieu of more traditional quantitative decision models for R&D portfolio selection. An extensive review of the literature revealed that decision models inadequately address the risk and uncertainty inherent in R&D. The approach taken was to develop a decision support methodology that would assist the Air Force space technology advocate to determine the strategic and technical utility of space technology issues. To do this the R&D environment was analyzed and hierarchically modeled. From this model criteria were developed that could be used in a worth assessment of space technology issues. Using these criteria the decision maker can focus on the strategic appreciation of the technology issues and their relative worth to military space strategy and doctrine and military space technology.

A description was presented of the information requirements and the analytical tool (the analytic hierarchy process) which could be used by the decision maker, with the appropriate user interface, to apply the criteria in a worth assessment of space technology issues. This worth assessment, in conjunction with an appreciation for the external factors in the decision situation, allows the decision maker to develop a space technology advocacy plan that is based on

doctrine and on an appreciation for the strategic nature of the problem. The results of testing the validity, adequacy, and suitability of the proposed methodology are presented. Eight space technology experts applied the criteria to sets of space technology issues within the context of the analytic hierarchy process. The results indicate that the proposed methodology provides a firm foundation for development of a microcomputer-based decision support system.

A DECISION SUPPORT METHODOLOGY FOR SPACE TECHNOLOGY ADVOCACY

I. Introduction

> Technology itself does not automatically confer military advantages, and a blind faith in technology uncoupled with strategic analysis and deliberate participation in the Technological War can lead to disaster. It requires a deliberate strategy [187:5].

Background

Space Technology demands a strategy for advocacy. This strategy would be a mechanism for integrating goals, tasks, and priorities for military space R&D programs. We propose a decision support methodology for space technology advocacy that is based on doctrine and technological potentials. This, we hypothesize, will be more efficient and effective than current quantitative R&D decision models. This section develops our efforts to model the space technology decision situation.

We began this research effort on the request of the Air Force Space Technology Center (STC). STC had developed a space technology database and plan called the Military Space Systems Technology Plan (MSSTP). A resource allocation model called the Technology Resource Utility Management Process (TRUMP) was a set of decision rules that used the database to develop resource constrained technology plans. Initially, our efforts were directed toward improving and expanding the capabilities of TRUMP.

We completed an extensive survey of the management science literature looking for R&D resource allocation models that might have application to our problem. We learned that there are hundreds of R&D decision models and that most of these models inadequately address important R&D issues. It became evident that R&D resource allocation problems were too complex to adequately model with a quantitative decision model. This led us to explore decision support as an alternative approach to the space technology problem.

Research Problem and Scope

R&D processes are inherently strategic in nature. They are characterized by multiple and conflicting objectives and priorities in an environment that is complex, dynamic and uncertain. Furthermore, R&D projects are usually comprised of activities which are by their very nature nonrepetitive and noncomparable, and therefore information tends to be subjective in nature. Decision models do not adequately account for the varying degrees of subjectivity in predicting possible outcomes. As Quade [189:xii] states

> In concept it might be possible to develop a clear-cut set of decision rules that would apply to a set of specific problems and use these rules to carry out relevant and competent analyses to the level of detail needed. In reality, however, we find this completely impossible and believe that it will never be possible.

Along these same lines, Shannon [218:246] states that the inability to completely understand the dynamics of both

the problem and the decision-making process prevents us from designing systems or models that successfully aid the decision-maker.

One remedy for this deficiency in the techniques is to increase the sophistication of the models (i.e. the ability to handle more complexity) by interfacing the decision maker with some powerful analytical techniques into a decision making team. The analytical techniques must provide the decision maker with a mechanism to deal with the inherently subjective nature of R&D decision situations. This is best done through decision support. Decision support is a way to structure the problem so that the decision maker can more easily and rapidly consider the data and make better informed judgments which hopefully lead to better decisions.

Our proposed decision support methodology for use by the Air Force Space Technology Advocate is designed to provide the following features [116:146-147]: meaningful reduction of available information; aid to eliciting subjective preferences and judgments; better insight into the various value judgments; inclusion of differences in interest and/or political views; alternative modeling of the R&D process; aid to substantially better considered decisions; aid to better group decisions and interaction; more controllable position of the Space Technology Advocate; more justifiable basis for policy decisions; and a microcomputer based decision making aid.

Research Approach and Presentation

We develop a space technology advocacy model (Figure 1-1) that depicts the important interactions in the space technology advocacy decision situation. From a comprehensive description of the space R&D decision environment we develop criteria with which to evaluate the strategic and technical utility of space technology issues. Strategic and technical utility is defined to be the worth of a technology issue in the context of its possible contribution to military space strategy and doctrine and its contribution to space technology. The decision support methodology allows the decision maker to assess the relative worth of space technology issues by considering, through an appropriate user interface, the criteria and relevant information using an appropriate analytical technique. The analytical technique (the Analytic Hierarchy Process) provides a mechanism for the decision maker to evaluate the subjective judgments of space technology experts. The decision maker can then consider external factors before presenting his space technology advocacy plan.

Chapter Two of this thesis is a comprehensive summary of the available literature on risk and uncertainty, elicitation of subjective preferences, and R&D portfolio selection models. We first discuss the strategic nature of R&D processes and emphasize the characteristics (risk and uncertainty) that most complicate the analyses from an operations research or management science perspective.

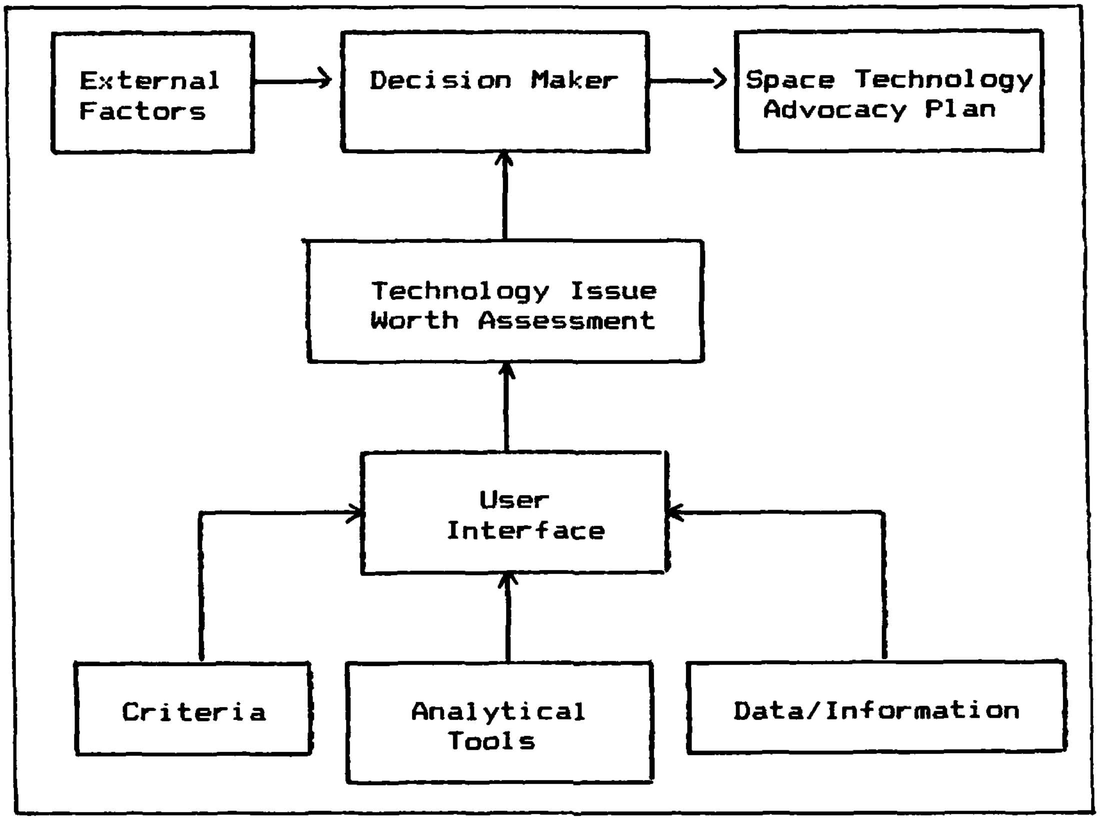

Figure 1-1. Space Technology Advocacy Model

Next, we discuss how subjective judgments are elicited and used in R&D decision models. Finally, we present R&D decision models and show that these models inadequately address the complexity of R&D decision processes. Decision support provides an alternative approach to modeling the R&D process.

Chapter Three is a detailed discussion of the MSSTP and TRUMP. First, the elements of the MSSTP and TRUMP are presented followed by a discussion of STC's attempts to implement MSSTP and the eventual abandonment of TRUMP as a resource allocation model. Throughout this chapter we focus

on the problems with quantitatively modeling a complex process in an uncertain environment.

Chapter Four focuses on the linkage between doctrine and space-related R&D. We present a more expanded description of the space R&D environment. Several environmental factors are discussed which ultimately tie the R&D process to satisfying national interests.

In Chapter Five we present a hierarchical structure to model the space R&D process. From this model we develop three criteria for evaluating the strategic and technical utility of space technology issues. We show the linkage between this hierarchical structure and the space R&D advocacy model (Figure 1-1).

Chapter Six discusses the information requirements, the analytical tools, and user interface of the space R&D advocacy model. We describe the database, database management system, and the information required to make space technology issue assessments. Next, we show how the Analytic Hierarchy Process can be used to elicit the subjective judgments of space technology experts. The user interface is addressed in the context of guidelines for transforming the decision support methodology into a computer-based decision support system.

In Chapter Seven the results of an exercise in which several space technology experts used our proposed model to evaluate space technology issues, are presented. The participants' responses to a questionnaire are discussed.

In Chapter Eight we present results and implications of our research effort. Based on these results, we reach some conclusions concerning our proposed decision support methodology. These conclusions tie in with our recommendations for future research.

> Military (space) technology should begin with strategic appreciation. The strategic appreciation provides the strategist with an estimate of the probable outcome of present trends, and allows him to form judgments about the future requirements and capabilities for military technology. It thus forms the first step. The second step comes from the scientific community in the form of possible or probable developments in the world of technology [187:64-66].

II. Survey of R&D Portfolio Selection Techniques

Introduction

Our review of the literature was first oriented towards identifying the various methodologies that have been developed to support R&D acquisition and resource allocation decisions. We extensively examined the management science literature to identify quantitative decision models that might have application to the space technology advocacy problem. Concurrently, we initiated a DTIC (Defense Technical Information Center) search to determine what efforts had already been taken within the DoD and other governmental agencies to manage the risk and uncertainty in defense related R&D programs. At the same time we began an indepth analysis of the Military Space Systems Technology Plan (MSSTP, covered in Chapter Three).

Our research showed there were many problems with quantitative approaches to analyzing R&D processes. While hundreds of models have been suggested, there is no consensus within the management science community as to which models or categories of models are best for analyzing R&D related problems. We learned that R&D processes are particularly difficult to model because of their inherent complexities. We then reoriented our research to determine the nature of these complexities.

Following this reorientation we learned that R&D processes are strategic in nature. They are sequentially

staged; in the early stages operating in an environment of great uncertainty, unspecified organizational goals, and no analytical database from which to project future outcomes. As R&D efforts progress over time, the environment changes, with more information becoming available from which to base more accurate predictions and forecasts. Thus R&D processes are dynamic and vary in degrees of uncertainty. Because of the great uncertainty prevalent in the early stages of these processes, most decisions are based on subjectively derived data, elicited in a variety of ways. We then directed our efforts into determining how uncertainties were handled within this context. We learned once again that there is no consensus among management scientists on the very definition of uncertainty, or how best to apply quantitative analyses to account for uncertainty. Furthermore, while most authors agreed that subjective judgments were the primary source for estimates of uncertainty, there was no agreement on how best to elicit these judgments.

Ultimately our research led us to conclude that because of these complexities, one must first define the decision situation and environment and then define the appropriate decision support structure within which to analyze the problem. Since the primary objective is to identify high priority space technology issues, we needed a decision support structure that adequately models the early stages of the R&D process where uncertainties are more numerous and subjective inputs more critical. This drove our effort

towards developing a suitable methodology that captures subjective judgments in an environment of high uncertainty and little quantitative data.

This chapter represents a summary analysis of our literature research. In the interest of brevity, we have intentionally kept the discussion concise. Where applicable, we indicate other sources which expand on points made in our discussion. We first discuss the strategic nature of R&D processes and emphasize the characteristics that most complicate the analyses from an operations research or management science perspective. Uncertainty, which is one of these characteristics, is treated in some detail. Not only do uncertainties contribute to the complexity of analyzing R&D processes, but attempts to "quantify" variables whose attributes are unknown must be based on the elicitation of subjective judgments. This naturally leads into a discussion of how subjective judgments are addressed in the management science literature and some of the documented problems with their application to quantitative R&D decision models.

Next, we present the results of our research into the various categories of management science methodologies that have been suggested or used to model R&D processes. We discuss the major characteristics, advantages, and disadvantages of each category. We show that there is no consensus among management scientists or users concerning which is the best approach, or whether quantitative decision models are

useful at all in analyzing complex R&D processes. We conclude that given the great uncertainties inherent in the early stages of R&D processes, an acceptable methodology for capturing subjective preferences is essential.

This leads into a discussion of methodologies we reviewed designed to elicit subjective judgments from decision makers. We explored two in some detail -- multiattribute utility theory (MAUT) [137] and the analytic hierarchy process (AHP) [198; 203]. We ultimately settled on the AHP as the best overall approach for capturing subjective preferences, according to criteria we set forth.

Finally, we discuss the benefits of applying the AHP within the context of a decision support methodology whereby the appropriate information and the AHP are interfaced with the decision maker in order to aid him in making better informed judgments about space technology issues.

The Strategic Nature of R&D Processes

R&D processes are concerned with the acquisition and allocation of resources applied to R&D efforts to maximize future benefits accruing to an organization. We categorize models intended to select R&D programs or research approaches to meet specified goals over a given planning horizon as "R&D Portfolio Selection" models. For a business whose future depends on successful development of competitive products, R&D Portfolio Selection models may be intended to provide management with a recommended list of

research efforts which will maximize profits in some future timeframe. In the military, these models may be used to identify technologies that provide the greatest potential military utility to satisfy future performance needs.

The general class of decisions that involve the acquisition and allocation of resources to maximize future benefits can be considered "strategic" if interactions between the decisions, the organization, and its environment must be taken into account in analyzing or describing the process [99:121; 213:340]. Several authors describe the R&D process as complex because they are inherently strategic in nature [55; 79; 99]. However, all agree that, despite this complexity, it is vital to an organization to develop a technical strategy that links long-range research with the corporate objectives [32; 33; 61; 62; 70; 87; 100; 147; 172; 178; 191; 217; 225; 274; 275; 283; 285]. Chiu and Gear [55] list four characteristics of strategic R&D processes.

The first characteristic is that R&D processes involve "a variety of factors, some technical but others organizational, behavioral, and economic" [55:2]. Obviously, this characteristic is not unique to R&D processes. Many other strategic management processes must also contend with these factors. However, several authors cite the particular interactions between technologists and managers in their attempts to formulate organizational goals early in the R&D process. For example, McClarey [164] discusses that the difficulties in managing military R&D are often due to upper

level managers failing to accurately translate their understanding of corporate objectives and goals into the technical environment. He also points out that the scientists, engineers, and technologists often feel that they should decide what projects should be undertaken by the organization, since they have the technical expertise [164:1-2]. Rubenstein and Schroder [194] and Hogarth and Makridakis [120] address the impact of organizational, situational, and personal variables on the R&D process. They point out many of the biases and complex interactions between individuals at various levels within and outside the organization involved with the R&D process. Peters and Waterman [185] state that R&D must be "externally focused" to consider needs and demands from outside the organization [185:157]. Many other references also address the inherent complexities involved with interactions between these factors [17; 79; 114; 129; 130; 149; 160; 172; 181; 185; 192; 212; 232; 235; 238; 239].

The existence of multiple and conflicting objectives and priorities at various levels in the organization is the second characteristic cited by Chiu and Gear [55:2]. Like the first, this characteristic is not particularly unique to R&D processes. Several authors describe the inherent conflict in allocating resources for R&D and other organizational interests [32; 100; 185; 217; 275]. Alternatives are difficult to specify in any detail early in the R&D process [181:276] and R&D output is difficult to measure

since it is dependent on individuals more so than the equipment used [164:2]. In general, upper level managers are reluctant to expend resources for speculative R&D that may or may not reap future benefits for the organization. On the other hand, the emphasis on R&D should be on fast moving technologies of generic interest for meeting corporate objectives, technologies with payoffs that extend beyond the horizon of current operations, and promising ideas for which technical feasibility is in doubt and risk is high. Hence, there is this inherent conflict within organizations over resource allocations to R&D and other interests of the organization [275:38].

A third characteristic described by Chiu and Gear is the sequentiality of complex interactions between projects and with the "outside world" [55:2]. Gillespie and Gear emphasize that the time scale of strategic decisions is usually measured in years, which makes it difficult to correlate outcomes with earlier forecasts and decisions. They further state that strategic decision processes follow a sequence over time as the organization adapts to changing circumstances [99:121]. Albala [14] notes that R&D projects progress sequentially through stages, with early stages being characterized by uncertainty and qualitative judgments, while later stages can be analyzed quantitatively as more data are collected and processed. He also hypothesizes that different methodologies should be used to analyze R&D processes at each of the various stages, that no one method

is suitable for evaluating the entire process [14:153; 156]. Moore and Taylor [175] similarly categorize R&D processes as multi-staged, citing problem definition, research activity, solution proposal, prototype development, and solution implementation as five distinct stages common to all R&D projects [175:402]. Others also address the sequential nature of R&D processes [95; 146; 212].

The final characteristic identified by Chiu and Gear is the varying degree of subjectivity involved in predicting outcomes of actions and estimating related probabilities [55:2]. A consensus of authors maintain that the key element that sets R&D processes apart from other strategic problems is the inherent degree of uncertainty [24; 55; 72; 79; 97; 99; 129; 192]. Uncertainty exists in how decision makers at all levels perceive probabilities for success [99:121], and how they perceive future economic, ecological, social, political and/or technological conditions [20:24]. The anticipated benefits from a project, the resources required, and overall resource availability are all subject to varying degrees of uncertainty [153:B581]. The only way analysts have found thus far to incorporate these uncertainties in their models has been to solicit subjective estimates from decision makers and R&D personnel [20; 99:121; 108:281; 153; 194:138]. Subjective estimates are generally biased and tend to be inaccurate and unreliable [39; 79; 109; 120; 194; 212].

In summary, R&D processes are strategic in nature. As

such, they are complex, dynamic, and uncertain. For the most part, predictions of outcomes and future conditions are based on subjective judgments which attempt to estimate the various uncertainties that are inherent in R&D processes, especially in their early stages. In the next section we explore uncertainty in more detail. We show that while many models attempt to account for uncertainty, there is no consensus among analysts on definitions or treatments for uncertainty when evaluating R&D processes.

Risk and Uncertainty, Is There a Difference?

As we showed in the last section, R&D processes operate in an environment of great uncertainty. Treatment of risk and uncertainty is a major concern within industry and the DoD, as evidenced by the number of symposiums that have addressed the subject over the last several years and the proliferation of risk assessment models that purport to manage cost, schedule, and performance risk. And yet our research showed that there is no consensus among the experts on operational definitions for risk and uncertainty [123; 125; 126; 129; 192]. Many authors use the terms interchangeably [40; 64; 84; 133; 195; 279], improperly [20; 286], or ignore uncertainty altogether [82; 93; 193]. Furthermore, while a number of risk assessment models exist, their use is not widespread within the DoD R&D community [125; 139; 211; 287]. Several authors stated that not understanding or accounting for the distinction between risk

and uncertainty in quantitative models ultimately leads to inaccurate and unreliable final results. This may partially explain why these models are not used more widely [125; 192].

In this section we develop an operational definition for both risk and uncertainty and provide examples of specific uncertainties that are characteristic of R&D processes. We also highlight some general drawbacks of methods designed to "quantitatively assess" uncertainty.

Risk and uncertainty are defined by many authors in probabilistic terms [111; 126; 129; 192]. From classical probability theory, risk can be defined as the condition where each decision of the decision maker leads to one of a set of specific outcomes, each occurring with a known probability. Likewise, uncertainty can be defined as a situation where the probabilities of the various outcomes are completely unknown. Under conditions of "extreme uncertainty", the outcomes themselves may not be knowable, or may not be anticipated if knowable [129:165].

Risk has been operationally defined in various ways, but the most accepted definition we found was that risk represented the level of consequences of a wrong decision and could be determined by multiplying the probability of failure with the consequences of that failure for any given goal [93; 126; 192; 193]. This concept of risk is the basis for decision analysis from which expected payoffs are calculated. For example, the probabilities of flipping a coin

and coming up heads is known to be 0.5. If I am offered five dollars for a "heads" (and nothing if the coin toss results in a "tails") or a dollar if I do not flip at all, then I can calculate my expected payoff as (0.5)($5) or $2.50. When I compare this with the dollar I get if I do not flip the coin at all, and assuming I was not a risk averter, then I would choose to flip the coin and take my chances on winning $5. More complex and detailed analyses can be performed as well, so long as the probabilities are known (or can be determined) for each of the possible outcomes.

Uncertainty is not so easily defined in operational terms. The reason for this is fairly straightforward. If we adopt the classical definition from probability theory, then we have no way to measure, estimate, or otherwise quantify variables whose probability distributions are unknown. And yet, any attempt to more clearly specify uncertainty would be the same thing as saying you know something about the unknowable -- a clear inconsistency. Nonetheless, several analysts operationally define uncertainty as those situations in which "potential outcomes cannot be described in terms of objectively known probability distributions" [111:217] or as the "relative unpredictability of an outcome of a contemplated action" [192:10]. Others still choose to ignore uncertainty altogether in their analyses of R&D processes [133; 149; 279].

Lilge [150], in his evaluation of TRACE, a methodology

used by the Army for managing R&D programs, provides an excellent discussion on this quandary of how to operationally define uncertainty. He quotes Gene Fisher [150:5], who offered the following definition:

> Oftentimes probability distributions are assigned to uncertain situations, but these are of necessity subjective in nature. That is, they are based on the personal judgment and experience of the analyst, the decision maker, or someone else regarding the relative "likelihood" of unknown events. They are not based on incontrovertible empirical or theoretical derivations... If the latter were the case, we would be dealing with a risky situation and the distribution would be called an objective probability distribution [150:5].

Lilge further points out that if this definition is taken literally, uncertainty analysis would be impossible, since distributions for uncertain situations derived from subjective judgments are not based on "incontrovertible empirical or theoretical derivation" [150:7]. Lilge contends that the problem can be circumvented by aggregating unknowns and deriving probability distributions from an analysis of historical data without reference to the specific unknowns [150:8]. In other words, uncertain variables are "clumped" together and a probability distribution is determined by analyzing historical data that includes the aggregate affects of the unknown variables. Thus uncertainty can be analytically treated the same as risk. This is in fact how several methodologies handle uncertainty. Several examples of this class of methodologies are TRACE [15; 25; 107; 150], VERT [37; 173], PROMAP V [84], and DARPA Risk

Assessment [126; 127; 168; 169; 221].

There are some inherent problems with even this operational definition, as we point out shortly. To maintain the essence of uncertainty, we elect to use the definition cited above by Fisher, who notes that of necessity, probability distributions are often assigned uncertain information, but that these are subjectively derived and will not stand up to the rigors of probability theory.

As we mentioned earlier, R&D processes are frought with uncertainties, especially in their early stages. It is beyond our scope to address all of the types cited in the literature. However, some excellent survey articles are available that describe most in some detail [125; 192; 287]. We briefly describe a few of the more important uncertainties that impact the R&D process.

Rowe and Somers [192] in an excellent survey article on the history of risk and uncertainty in the DoD discuss a variety of uncertainties that impact the R&D and acquisition processes. Somers [232] relates these in a causal-integrative model that depicts the interactions between uncertainties and other environmental factors. The uncertainty factors described by Rowe and Somers, which were developed originally by the USAF Academy Risk Analysis Study, are internal program uncertainty, technical uncertainty, process uncertainty, and target uncertainty. Each is discussed below.

Internal program uncertainty deals with the

way in which the program is organized, planned and managed. Several types of uncertainty exist within this factor alone, namely, uncertainty of the initial estimate and its impact on program management, uncertainty in the acquisition strategy and outcome, uncertainty in resources needed, flexibility, or lack of contingency plans. Also, competing demands, including conflict between reliability, vulnerability and maintainability with performance and operating costs are addressed under this category.

Technical uncertainty covers the feasibility of developing the system at all, including the degree of technical difficulty. It generally starts with an optimistic estimate of the state-of-the-art and often leads to a slippery technical baseline.

Process uncertainty deals with the sensitivity to changes in the external environment such as changes in priorities or policies and budget considerations. The unavailability of funding or other resources when they are needed, the effects of inflation and government regulation, and the uncertainty in the criteria that are used for changes add to process uncertainty.

Target uncertainty is the uncertainty in meeting performance, cost or schedule goals and determination of needs as well as the uncertainty in translating abstract needs into concrete specifications. The problem of early estimates which are seldom revised is one example of target uncertainty [192:8-9].

Many other authors include elements of the above uncertainties in their discussions. For example, cost uncertainty is frequently listed as a separate category [28; 107; 125; 133; 211], as is schedule uncertainty [28; 40]. However, the four categories listed above capture the majority of uncertainties prevalent in acquisition and R&D processes.

We mentioned earlier that one method that many models

use to account for uncertainties is to aggregate all unknown variables into a single distribution and estimate distribution parameters based on analysis of historical data. There are two problems with this approach. The first is that it often takes too much time and effort to collect the data necessary to make meaningful analyses [99:128; 107:69-70; 125:61]. Secondly, and perhaps more importantly, R&D programs are normally unique, no two are alike in every respect, and historical data (if available) may not be a good indicator from which to draw any useful conclusions [14:153; 24:125; 39:15; 55:7; 79:109; 107:72; 168; 169].

This leads back to the use of subjective judgments for deriving probability distributions for unknown (uncertain) variables. Most risk assessment and R&D portfolio selection models use subjective judgments, elicited in a variety of ways. Once again, however, there is no consensus among management scientists on how best to elicit subjective judgments and account for biases, or whether eliciting subjective judgments is even worthwhile [49; 79:109; 194:137; 238:48]. The next section addresses these points.

Subjective Judgments and Subjective Probabilities

Subjective inputs are extremely difficult to quantify because they basically represent the feelings of the decision maker "as to the relative importance of a set of criteria each of which can be attributed to each of a set of alternative options in varying degrees" [96:11]. A large

number of authors use the term "subjective probability" to represent "degrees of belief and state of mind" [53:327; 79:108; 97:72; 109:12; 139:200]. An operational definition of subjective probability is provided by Budnick, et. al. [44:704]:

> An approach to the assignment of probabilities is to use subjective opinion. This procedure allows for the translation of the experience and feelings of the decision maker into an estimate of the likelihood of occurrence of an event. This form of "educated guessing" can be effective in actual practice, for example, determining odds for sporting events ("Jimmy the Greek"?) and the estimation of success levels for new products by brand managers.

Chesley [53:326] provides a more formal definition when he states that "subjective probabilities are a measure of the confidence that a particular individual has in the truth of a particular proposition."

In general, subjective probabilities are the result of a transform that converts qualitative judgments, opinions and beliefs into numerical values that should represent the decision maker's evaluation of the probabilities of success, occurrence, failure, etc. of an event. Subjective probabilities become the quantitative measures of "feelings" or uncertainties that allow analysts to mathematically model R&D processes.

Considerable research attempted to provide a theoretical basis for proving the validity of subjective probabilities. Chesley [53] authored an excellent survey article on the subject. However, many still argue that the axioms of

rationality have not been met [129:166; 185] and that biases will adversely affect the accuracy or consistency of subjective judgments [109:14; 120:117; 194:137; 238:36]. A detailed discussion of the various points and counterpoints can be found in the references. Again, there is no consensus on the ultimate validity of subjective probabilities as a reliable indicator of "real world" occurrences [39:15; 129:166; 194:142; 238:48].

It is worthwhile, however, to note that many methodologies attempt to quantify subjective preferences. Subjective judgments are elicited in various ways [28; 53; 79; 133; 212]. The most prevalent methods are: direct interview with experts or responsible individuals to solicit their "feelings" concerning probable outcomes; review of available historical records for similar activities; delphi-type approaches to solicit group preferences; and multiple estimates to fit to a Beta distribution [212:44-45]. Of the four mentioned, the multiple estimate method seems to be the most widely used [28; 36; 82; 133; 221]. We do not include in our discussion here methodologies designed specifically to elicit utility functions to represent preferences. This subject is covered later in the discussion on methods to elicit the subjective preferences of decision makers.

Unfortunately, most models fail to accurately solicit or project subjective probabilities [24; 79; 94; 109; 139; 194]. As noted by Ebert, "depending on the sensitivity of the decisions to errors in subjective estimates, the

ultimate success or failure of a project may depend on the quality of subjective estimates" [79:108]. The key factor in successfully using subjective probabilities then is to ensure high quality initial subjective estimates. This is where most models fail [79; 99; 139; 194; 234; 237].

Rubenstein and Schroder [194] state that two serious problems relating to the subjective character of these probabilities contribute to the low acceptance of models. First, there is the problem of the low reliability and validity of probability assessments -- the degree of association with actual projected outcomes. Secondly, the subjective probabilities, by their very nature, may vary from person to person and thus lack uniqueness [194:137].

Hogarth and Makridakis [120:125] in an excellent survey article on forecasting and planning note that:

> Before one can articulate a probability number which really reflects his true appraisal, he has to "know" how he feels. Becoming aware of one's own true feelings is by itself a very heuristic process. It involves self realization and self awareness of one's inner value system of feelings and sentiments.

Solicitation of feelings concerning an individual's value systems and beliefs, including those motivations that the assessor himself may not be cognizant of, can be a very difficult task. Several authors note that oftentimes solicited data is biased and unreliable [24:125; 120:127]. Biases can also be generated by external factors. Rubenstein and Schroder [194] list several and comment that biases and "interpersonal differences are the joint effect

of personal, organizational, and situational variables" [194:138]. Hogarth and Makridakis [120] provide an in-depth analysis of information process biases and address 37 separate biases found in various stages of modelling the R&D process. Much of the literature indicates that biases, and the modeler's failure to properly account for them, are the leading causes for poor subjective probability estimates.

Unfortunately, there is no consensus in the literature on how best to counter biases, or even if they should be countered at all. Advocates of scoring techniques [1; 79; 89] state that differences between actual subjective probabilities and "communicated" (biased) subjective probabilities can be quantitatively measured and corrected. Not all agree with this position [72; 97; 120]. Even if biases could be adequately accounted for, scoring may not be a valid method since the technique calls for a feedback and evaluation phase, which is dependent on collection of past performance data. Since each R&D program is unique, applying past data to current programs may be misleading [55:7].

Other techniques ignore the question of bias altogether, stating that simple quantitative methodologies such as linear or stochastic programming give adequate results in spite of the uncertainty of subjective probabilities [49; 97; 120]. One author states that decisions made on the basis of poor and biased estimates are likely to be bad with or without a model. However, he goes on to say that the

"adoption of a model leads to consistency -- both of data inputs and of decisions. With time and patience this very consistency of method may lead to a pinpointing of both the errors of estimation and, more importantly, the reasons for them" [153:B589]. There are many other experts who believe mathematical models cannot accurately account for uncertainty and that emphasis should instead be given to the process by which inputs are solicited [20; 72; 90; 162]. Chesley [53] provides a comprehensive discussion of elicitation techniques and concludes that the *nominal group method* is the best overall for accounting for biases where group interaction tends to negate individual dominance and other biases. However, when considering group assessment, Chesley says several factors should be considered, including the cost of assembling a group, leader-follower relations, game theoretic strategies, the problem of reaching a consensus, and the distribution of risks [53:333]. Gustafson, et. al. [108] document the results of statistical experiments that clearly show the superiority of nominal groups over Delphi and interacting groups. Nominal group members first estimate individually, then discuss their results and then estimate as individuals one last time. This allows for the benefits of group discussion and avoids the detractions of potential bias or influence from group members. Several other authors cite the *nominal group method* (or variants) as the best methodology for soliciting subjective probabilities [90; 162].

In summary, there is no consensus in the literature on how best to deal with subjective judgments and probabilities. There is unanimous agreement, however, that a great amount of descriptive work remains to be done in the area of uncertainty and subjective probability estimation. "So far no one has succeeded in describing the realities of R and D project selection in a thorough and detailed manner" [24:125].

Decision Models for R&D Portfolio Selection

R&D portfolio selection problems are difficult to model because of the uncertainty associated with R&D programs. Uncertainty is usually quantified by converting the decision maker's feelings, beliefs and opinions into subjective probabilites -- numerical values that can be entered into an appropriate mathematical model. However, because feelings are difficult to accurately communicate and because of external and internal biases, subjective estimates are frequently found to be less than adequate. In the minds of many analysts, this tends to negate the value of quantitative decision models for R&D portfolio selection problems. Others believe that decision model results are still valid, despite inherent uncertainties and biases on the part of probability estimators.

To avoid confusion we distinguish between decision models discussed in this section and decision support, which is discussed in the next section. Decision models are

designed to accept input data and then calculate or output "the optimal answer" or R&D portfolio. On the other hand, decision support is designed only to improve the effectiveness of the decision maker by supporting, rather than replacing, managerial judgment [136:1]. Decision support does not output an "optimal answer."

According to Albala [14], an examination of the relevant literature reveals that only a very few proposed decision models have found favor with R&D managers. This was first noted in 1957 [14:153] and since that time, there has been a continuous creation of new methods and techniques. However, the utilization factor for these methodologies still remains extremely low [24; 159; 190; 233].

Furthermore, Baker and Freeland [23:1165] identify the inherent limitations of these R&D decision models which adds to the low utilization rates. Each model exhibits to one degree or another these various limitations:

1. Inadequate treatment of risk and uncertainty.

2. Inadequate treatment of multiple, often interrelated, criteria.

3. Inadequate treatment of project interrelationships, with respect both to value contribution and to resource utilization.

4. No explicit recognition and incorporation of the experience and knowledge of the R&D manager.

5. The inability to recognize and treat nonmonetary aspects such as establishing and maintaining balance in the R&D program (i.e., balance between basic and applied work, between offensive and

defensive activity, between product and process effort, between in-house and contracted projects, between improvement and breakthrough orientation, and between high risk-high payoff and moderate or low risk moderate payoff opportunities).

6. Perceptions held by the R&D managers that the models are unnecessarily difficult to understand and use.

7. Inadequate treatment of the time variant property of data and criteria and the associated problem of consistency in the research program and the research staff.

Despite these limitations there exist hundreds of various decision models [237] that have been applied to the R&D portfolio selection problem. Several excellent survey articles have appeared in the literature that categorize and describe the many R&D project selection methods [22; 23; 24; 49; 97; 127; 128; 182; 183; 232; 237]. Also, several case studies can be found in the literature that describe actual applications of various techniques [13; 38; 57; 60; 71; 83; 135; 171; 208; 209; 224; 284]. In fact, there are so many different models available that Souder [237:63] had this to say about the situation:

> It does not appear that a confusing plethora of models, with little basis for a manager to choose among them, exists in other management science areas to the degree that it does in the area of R&D investment planning models.

Not only is there a plethora of models but also several different ways to categorize these models [22:168; 23:1165; 220:25-132]. In this discussion we adopt the taxonomy of models proposed by Shepherd [220]. Basically, there exist at least four general literature areas that explore problems

in R&D portfolio selection or similar problems. These categories are capital budgeting, capital rationing, project selection, and multiple criteria optimization.

Along these same lines, the literature can be divided into two additional categories: single criterion approaches and multiple criteria approaches. These can be further broken down into those that deal with certainty and those that attempt to account for uncertainty. One further breakdown of model types are those that attempt to select the "best" alternative from a set of alternatives and those that are aimed at choosing a "best set" of alternatives. According to Shepherd [220:25] all of these categories lead to a natural hierarchical taxonomy of decision models (Figure 2-1) aimed at choosing among alternatives.

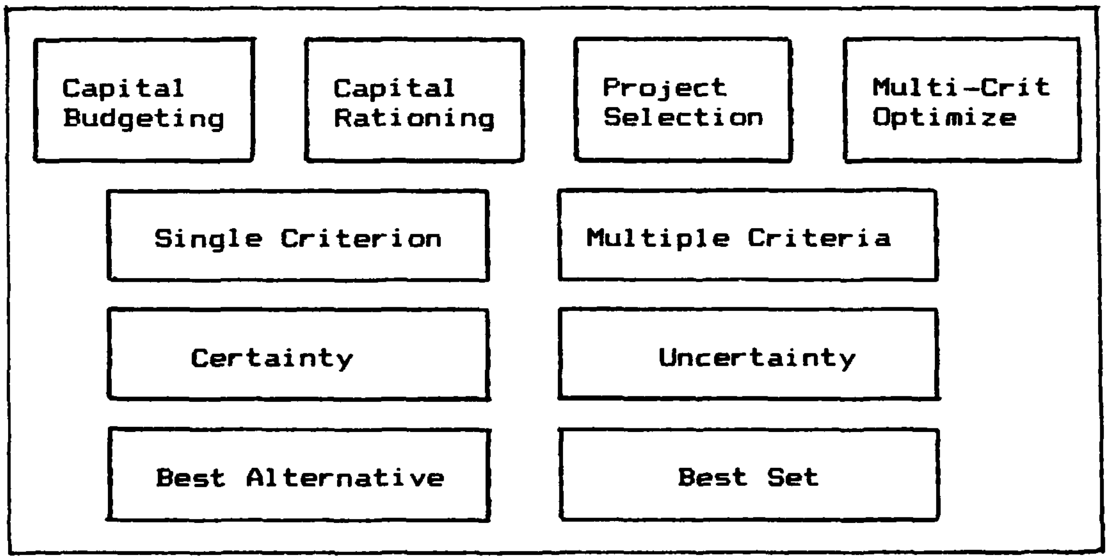

Figure 2-1. Hierarchical Taxonomy of R&D Decision Models

Decision models that attempt to select a single "best" alternative under conditions of certainty are the payback

method, average rate of return, internal rate of return, profitability index, and net present value. These models are concerned with one (usually economic) criterion for selecting the best alternative when possible outcomes are known with certainty. The above models are often called capital budgeting under certainty or project selection under certainty. Clark [56] describes a profitability project selection method. A return on investment approach is presented by Augood [19]. If used at all in the R&D portfolio selection problem, these economic methods are usually applied to product-oriented research [142:21]. However, none of these models are suitable for the space technology advocacy problem primarily because they ignore the pervasive uncertainty in the R&D decision situation. Their practical application is limited by the need for accurate input data (usually in dollars), and the fact that they cannot be used to analyze projects at different funding levels. More sophisticated models must deal with these multiple funding levels.

Models that deal with multiple alternative selection under conditions of certainty are Ø-1 integer programming, dynamic programming and quadratic integer or nonlinear programming. These models are called capital rationing if budgetary constraints are imposed on the formulation. Some of the models in this category allow for interdependent projects or alternatives. However, these models deal with optimizing against a single criterion and are inadequate for

dealing with uncertain decision situations. Again, a relatively large amount of information, usually expressed in dollars, is required for problem formulations. Also, the expected benefits from each R&D project must be quantified in such a way as to be consistent with the objective function. Along this same line, the resources required by each project must be carefully defined, as well as the limits to these resources. Examples of 0-1 integer programming models can be found in [58; 81; 97; 153; 157; 176]. Dynamic programming models are explored in [14; 34; 35; 97; 106; 128; 138; 188; 273]. Nonlinear models are described in [54].

The next general category of decision models are those that deal with uncertainty and attempt to optimize against a single criterion. Examples of these types of models are simulation [76; 156; 158; 175; 236; 250]; portfolio analysis [219; 236]; network models [76; 156; 186]; risk analysis [69; 102; 118; 192; 273]; chance constrained programming [97; 128]; mean variance; and mean semi-variance models. Within the military R&D environment simulation models include TRACE and VERT [15; 25; 37; 107; 150; 173] as well as PROMAP V [84] and PREDICT 2000 [149]. Again, none of these models adequately deals with the uncertainty in the R&D environment. The problem lies mainly in the manner in which probability distributions are generated which depends on large historical databases [107:69-70; 125:60-61].

A major area of research is in decision models that can deal with multiple criteria under conditions of uncertainty.

Models in this category are scoring models, profile reports, checklists, goal programming, multiobjective optimization techniques, dynamic programming, and utility models. These models show the greatest promise for evolving into decision models that can adequately address the complexities within the R&D community. For example Krawiec [142:22] lists five advantages of scoring methods.

1. Scoring methods are specifically designed to incorporate noneconomic criteria.

2. Scoring methods use input data in the form of subjective estimates provided by knowledgeable people as well as in the form of point or interval statistical estimates.

3. Scoring methods use subjective "guesses" overtly where other methods generally require a more costly and sophisticated quantitative form of the same "guess."

4. The subjective probability assessment can be built into the conceptual and analytical framework of the scoring method to produce an efficient portfolio of R&D projects.

5. The scoring methods produce results that are, on average, 90 percent rank-order consistent with economic and constrained methods.

In general, the same points can be made about the other methods in this category. Examples of scoring methods can be found in [1; 66; 73; 79; 89; 110; 134; 152; 172; 174; 177; 223; 251; 276; 277; 278; 282]. Profile reports are described in [85; 131; 277]. Three different checklists can be found in Becker [29]. Examples of applications of goal programming are found in [59; 124; 196; 226; 249; 281]. Theoretical foundations of multiobjective optimization techniques (MOOT) as well as other multicriteria decision making

techniques can be found in Chankong and Haimes [50; 51], Hirsch [117] and Zeleny [288]. Examples of the application of MOOT are addressed in [3; 94; 98; 116; 165; 166; 222; 281; 289]. An interesting observation about these MOOT applications is that they are combined with a utility model for eliciting the subjective estimates from the decision maker. These estimates then become the parameters within the multiobjective problem formulation.

Although many other methods exist such as fuzzy set theory [27; 30; 88], stochastic linear programming [55], factor analysis [252], and discriminant analysis [26], all share the same set of limitations discussed earlier [23]. In particular all are dependent on subjective judgments for model inputs. We now discuss two alternative methods that are specifically designed to elicit the subjective judgments of the decision maker.

Comparison of MAUT and AHP

The two methods that we discuss in some detail are multiattribute utility theory (MAUT) [117; 137; 165; 214; 215; 216; 244] and the analytic hierarchy process (AHP) [2; 119; 154; 155; 198; 199; 200; 201; 202; 203; 204; 205; 214; 215; 261; 262; 263; 264; 265; 266; 280]. MAUT and AHP are designed to transform noncommensurable criteria into a personal preference scale (also known as a utility scale or utiles) [151:330]. The theoretical foundations for MAUT can be found in the excellent text by Keeney and Raiffa [137].

Those interested in the theoretical development of AHP are referred to the two works by Eckenrode [80] and Saaty [198; 203]. Eckenrode discusses various ways of weighting multiple criteria whereas Saaty develops a method of pairwise comparisons (the AHP) to weight multiple criteria.

We have selected AHP as the methodology for eliciting the subjective preferences and judgments of the experts. To support this choice we feel it is necessary to compare the methodology to MAUT. MAUT is well supported in the literature and has a strong theoretical foundation. It has also been developed into highly interactive computer programs [244]. However, from our own personal experience with using both MAUT and AHP, as well as the work done by others, the AHP performs better according to the following criteria: ease of use, ability to deal with both quantifiable and strictly nonquantifiable and subjective variables at the same time, ability to capture preferences, and applicability to group decision-making situations.

Schoemaker [214] discusses behavioral issues in multiattribute utility modeling and decision analysis and compares AHP and MAUT. Schoemaker and Waid [215; 267] experimentally compare different approaches to determining weights in additive utility models of which MAUT and AHP are two. Gear, Lockett and Muhlemann [96] discuss AHP in the context of group problem solving and highlight the advantages of the AHP over MAUT. The results of these comparisons and experiments clearly show that AHP performs better

than MAUT according to the four criteria discussed above. Gear, Lockett, and Muhlemann [96:18] summarize the advantages that AHP has over the more traditional MAUT.

1. Instead of repeated questioning to eradicate inconsistencies in a mathematical sense, a simple measure of consistency is calculated and presented to the decision maker. He can then choose to attempt to improve his consistency or continue with a degree of inconsistency.

2. The -9 to +9 ratio scale allows fuzzy variables to be easily handled together with more closely defined and quantitative variables.

3. The algebraic method allows the calculation of a set of weights in spite of the fact that the subjective answers imply a degree of inconsistency.

4. The method naturally lends itself to self-use through an interactive computer package.

5. The same basic method may find application in several areas related to the R&D portfolio selection problem. In particular, to aid the calculation of the relative overall utility of project outputs, and to generate subjective probability assignments for chance intermediate and final outcomes of each project.

6. The method is very suited to use in group decision-making situations, perhaps combined with some form of Delphi procedure (or nominal group process).

To summarize to this point, given the lack of consensus concerning optimum methods for solving R&D portfolio selection problems and the varied opinions voiced on the validity of subjective estimates, it appears that our research effort must clearly address how we intend to deal with subjective inputs and how best to minimize the effects of biases and uncertainty. We do this by developing a decision support methodology that structures the decision

environment hierarchically, employs the analytic hierarchy process for the elicitation of subjective preferences, and describes the data and information requirements for supporting the decisions of the space technology advocate. The next section investigates the literature dealing with decision support and how it can be used in R&D portfolio selection.

Decision Support Methodologies

The recent trend in the application of analytical techniques to the R&D portfolio selection problem appears to be away from decision models whereby the model purports to give the "answer". Instead, the trend is towards the development of decision information systems or decision support systems. Baker [22:169] and Baker and Freeland [23:1173] suggest three reasons for this trend. First, the project selection/resource allocation models we have discussed above do not include all the important and relevant aspects of the R&D environment. Second, the decision problem is usually of the multicriteria type with the typical approach to quantifying subjective preferences far from satisfactory. Finally, the R&D process is highly uncertain and unpredictable. Hence, the general managerial attitude to the normative models is that they are useful for the predictable activities but are totally inadequate for modeling the uncertainties that are an inherent part of R&D. This has led to the development of interactive, decision

information or decision support, scenario generating approaches that offer an alternative to the uncertainty in the R&D decision process.

This section briefly discusses decision support in terms of it being a distinctive concept and methodology for developing computer-based decision aids [136:viii] and the application of decision support to the R&D project selection problem. In Chapter Six we discuss the proposed decision support methodology in detail. However, the general philosophy behind decision support is discussed below followed by the identification of the various elements in a decision support system.

Decision support is aimed at improving the decision process with computer technology being the focal point. Keen and Morton [136:1] identify three objectives of decision support. First, decision support is provided to assist the manager in the decision process in semistructured tasks. Second, decision support does just that; it supports, rather than replaces, managerial judgment. Finally, decision support is intended to improve the effectiveness of decision making rather than its efficiency. In the context of the R&D process the philosophy of decision support is that the manager is better equipped to define the problem and to handle the uncertain and subjective factors. According to Liberatore and Titus [148:973] the attention should be towards developing techniques that assist the decision-making process rather than attempting to optimize.

These techniques that assist the decision-making process can be categorized into three general areas. First, the decision support system must provide the decision maker with access to the appropriate information, usually in the form of a database. Second, the decision maker uses this information in conjunction with one or more analytical tools in order to gain further insight into his decision problem. The analytical tool we use in our proposed methodology is the AHP. The third element is the user interface. This can be the most critical part of the decision support system [16; 46; 52; 74; 101; 113; 136; 141; 145; 159; 184; 243; 245].

The remainder of this thesis is directed at developing a "user friendly" decision support methodology for space technology advocacy which is acceptable to management and which can serve as a useful vehicle for studying the complexities of the problem from a management viewpoint. This methodology, in fact, could be built into a highly interactive decision support system that would be responsive to the needs of space technology planners.

III. Discussion of the MSSTP and TRUMP

Introduction

In December 1979 Lieutenant General Richard C. Henry, Commander, Space Division, Air Force Systems Command, directed a framework be developed from which to advocate space technology issues. In 1981 this task was transferred to the Technology Plans Directorate of the recently organized Space Technology Center (STC) at Albuquerque, New Mexico. From these beginnings, the MSSTP (Military Space Systems Technology Plan) evolved.

The MSSTP was intended to be a "reference for planning military technology programs." It was developed to catalog space related technology information, forecast future threats and mission requirements, analyze technology needs for the future by identifying technological deficiencies, and recommend R&D programs to correct these shortfalls [170b:1-1]. The purpose of the MSSTP was to communicate and focus space technology needs so that the necessary technologies would be available to support military requirements of the future [170a:ii].

The first edition of the MSSTP was published in January 1982. Since that time it has undergone significant changes in direction, scope, and content. The MSSTP started as an ambitious attempt to describe a methodology for "optimizing investment of space resources" [227]. It was originally designed to quantitatively derive a prioritized list of

resource constrained technology programs through an algorithm called TRUMP (Technology Resource Utility Management Process). However, as of this writing, the major emphasis of the MSSTP has shifted from prioritizing specific programs to prioritizing the technology issues themselves. In the words of Lieutenant Colonel Pete Soliz, a primary mover in developing the current direction and scope of the MSSTP, the only thing that can be said with any certainty concerning the MSSTP is that "it is a dynamic and iterative process" [230].

Despite these changes, the MSSTP today represents a significant and unique contribution to space R&D advocacy. The forty man-year effort that has gone into the MSSTP thus far has resulted in a fairly comprehensive and continually growing database of space related technologies. This database is particularly useful to space system designers and long-range planners when considering future military requirements that can potentially be met by space-based systems. Technology assessments in the MSSTP also assist R&D advocates attempting to secure funding and support for various technology initiatives with potential space applications.

Since our methodology (presented in succeeding chapters) builds upon the work already accomplished in creating the MSSTP, we take the time here to explain the process in some detail. The next section describes the MSSTP (as published) and TRUMP. This then provides the

foundation for further discussion of the space technology process. Next, we discuss STC's attempts to implement MSSTP, which serves to highlight the dynamics of the process. Finally, there is a discussion of some of the shortfalls of both early MSSTP efforts and TRUMP. Throughout this discussion we focus on the problems with quantitatively modeling a complex process of this sort in an environment of uncertainty. This discussion leads to our proposed methodology, which is an alternative approach designed to better cope with the uncertainty and subjectivity of space technology advocacy.

Overview of the MSSTP and TRUMP

The ultimate goal of space technology planning is to "ensure that an adequate technology base exists to support options for future U.S. military space systems" [170b:4-1]. The MSSTP is a framework from which to analyze R&D requirements, determine what are the most critical technology issues, and finally to develop a plan for resolving these issues.

An overview of the six volume set of the MSSTP is presented first. The emphasis is on showing how the process is designed to flow as a "network of interconnected logical processes" [170b:1-1]. A discussion of TRUMP concludes the section. Even though TRUMP is no longer used for prioritizing technology issues or programs, we believe it demonstrates some of the problems encountered in quantita-

tive analyses of problems of this magnitude and complexity.

The discussion is synthesized from published volumes of the MSSTP, MSSTP technology panel reports, and our interviews with STC personnel over the last several months. However, as previously noted, the MSSTP is a dynamic process and as such some of the information may change or has changed as of this writing. Interested readers should refer directly to the latest edition of the MSSTP for more current and detailed information.

The MSSTP. Figure 3-1, extracted from the MSSTP Executive Summary [170a:1-2], depicts the process described in the six volume set that is the MSSTP. For the most part, the volumes correspond to each of the five steps shown. "Assess Technology Needs" incorporates information presented in Volumes III and IV, while "Prepare Technology Roadmaps" includes both Volumes V and VI.

We give considerable weight to the discussion of Volume I, Mission Rationale, since this volume establishes the environmental framework within which the MSSTP process operates. Remaining volumes are addressed in less detail.

Volume I, "Mission Rationale". The opening volume lays the groundwork for subsequent volumes by discussing the environment in which space technology planning takes place. It argues that space technology must be responsive to national policies, international agreements and laws, and operational military requirements. Its primary purpose is to identify military tasks that could use space systems to

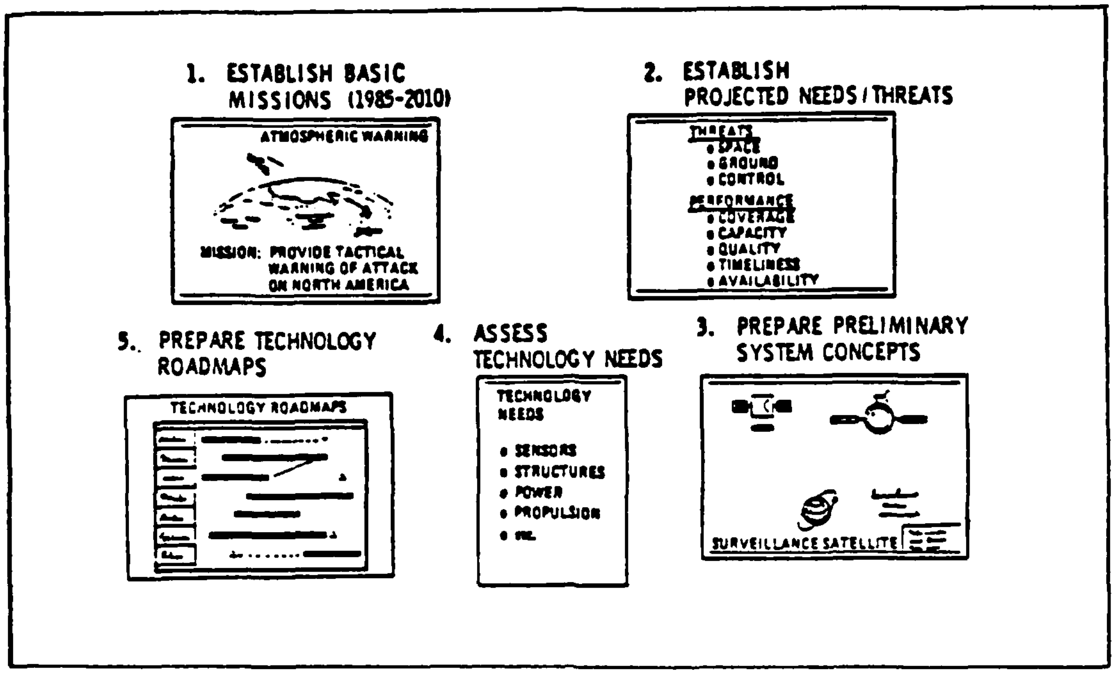

Figure 3-1. The Space Technology Model Process

accomplish military missions in the 1985-2010 timeframe. Potential space system concepts can then be linked to these military tasks to demonstrate how they could support operational requirements. Tasks selected in Volume I determine the quantitative performance needs for system concepts described in Volume II. Shown in Figure 3-2 [170a:I-2] is an overview of the methodology covered in Volume I:

<u>Task Derivation</u>. National policies and international laws and agreements dealing with the use of space constrain what tasks can be performed in space. Air Force doctrinal statements discuss the specific restrictions concerning use and deployment of certain military systems in space and specify military space responsibilities and

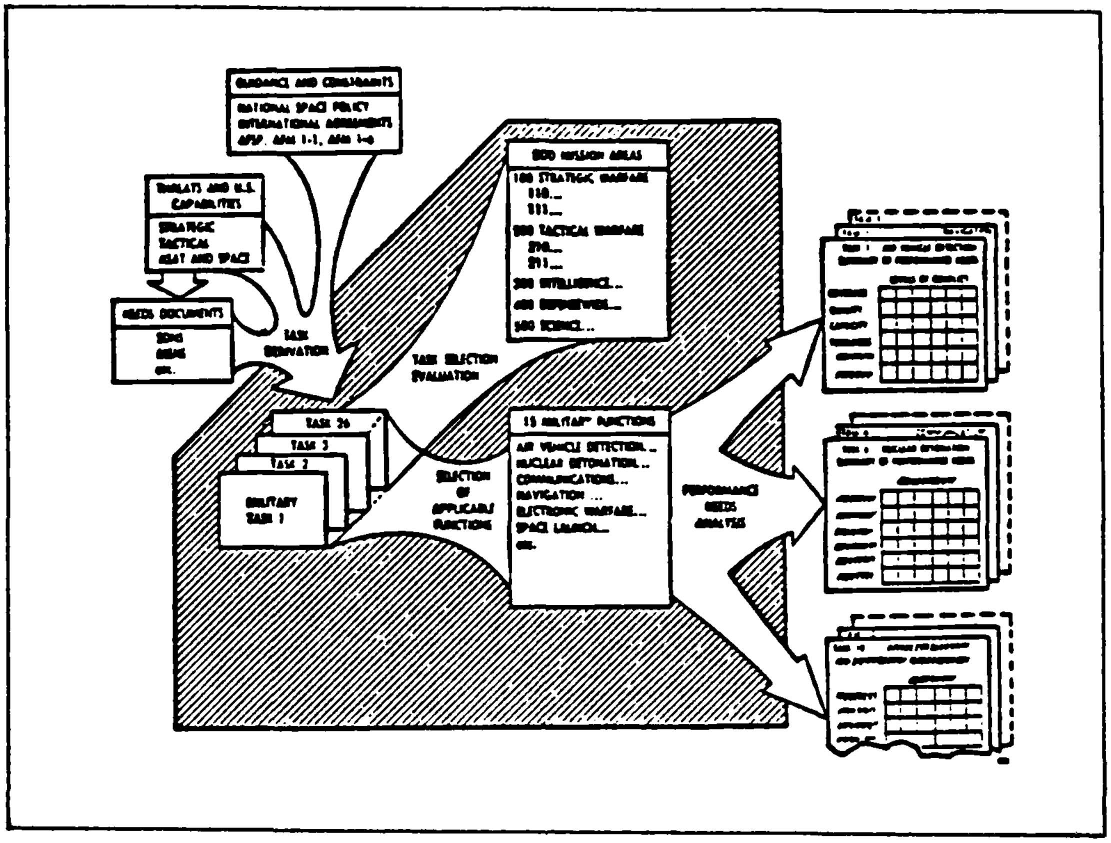

Figure 3-2. MSSTP Volume I Methodology

missions that are bounded by these restrictions. Essentially, doctrine specifies military responsibilities in space. These responsibilities then identify tasks which can be accomplished to support military missions in space. Ultimately, these tasks are constrained by existing policies, international agreements and laws, and doctrine.

Despite these constraints, Volume I cites the importance of flexibility in selecting tasks. Constraints can be dynamic and usually change as national interests evolve. "It is a major function of the technology base to support a

wide range of potential decisions concerning national interest and policy" [170b:2-1]. Additionally, the technology base must provide a hedge against technological surprise and support future expansion of military operations into space [170b:2-14]. Volume I further suggests that analyzing U.S. capabilities and projected Soviet threats is a way to identify future operational requirements.

First, the threat is analyzed with respect to current and projected Soviet capabilities in space. Volume I summarizes the Soviet threat in space, deriving information from a number of intelligence estimates and threat documents [170b:3-2]. The general findings are that the Soviet threat is severe in terms of quantity, quality, and kinds of systems employed by the USSR. The Soviets have made extensive use of space and have developed a quick reaction capability and flexibility in the employment of their systems. Estimates concerning these specific projected Soviet capabilities are then detailed.

Next, formal operational needs statements submitted by various commands and operational users are considered. Statements of Operational Need (SONs), Mission Element Needs Statements (MENS), and Required Operational Capability statements (ROCs) were reviewed to determine future space capabilities needed to support missions and tasks covered in these statements. Tasks listed or implied in these sources were extrapolated to include future, long-term needs.

Finally, taking the above factors into consideration,

Space Division analysts consulted the Air Force Planning Guide, which evaluates a large number of military tasks. Tasks are evaluated on the basis of current military capability and importance of the task to determine a priority for each task. Twenty-six candidate tasks that are potentially accomplished or supported by space-based systems were selected from this list of tasks [170b:4-3]. The complete task lists are provided in Appendix A.

It should be pointed out that there are some inconsistencies in task descriptions. Some represent desired objectives ("ballistic missile accuracy enhancement"), others are missions and/or functions. We asked STC personnel to explain in greater detail how tasks were derived, and some of the problems encountered during the process. We learned that when Space Division analysts developed the list of tasks, they found they had a "mixed bag" with tasks overlapping mission linkages in the mission hierarchy. They found it difficult to establish clear delineation between tasks, in part due to the "large area of uncertainty", the fact that task derivation was an "immature area", and the "lack of doctrinal consensus" with respect to space as an environment where military operations could be conducted [144]. While STC personnel recognize the drawbacks with overlaps among tasks and between tasks, missions, and functions, they feel they have to work with what they currently have available. Lieutenant Colonel Dave Lange [144], who played a key role in developing Volumes I and II

of the MSSTP stated:

> The Air Staff, in the context of mission area analysis, will have to increasingly address the space arena as military dependency upon, and use of space continues to evolve in the future, but in the meantime we will work around the problem.

Evaluation of Tasks Against Missions. The next step in the Volume I methodology is to link the 26 tasks to DOD mission areas. The purpose is to show coverage of all possible triservice missions by linking tasks to missions and mission areas. Volume I uses a reference developed by the Under Secretary of Defense for Research and Engineering issued on 19 June 1981 ("Research, Development, and Acquisition Mission Areas and Mission Area Descriptions") that provides a comprehensive breakdown of DOD mission areas and program elements. Tasks are sorted according to mission areas and categories. Some mission areas are covered by more than one task, while others have no corresponding space related tasks assigned to them [170b:4-11].

TRUMP used this data to show connectivity between tasks, missions, mission areas and arenas to derive task and ultimately concept priorities. Task and mission area linkages to the 26 space tasks are listed in Appendix B.

Linkage of Military Functions to Tasks. Next a set of military functions which apply to the task list is derived. Military functions are defined in the MSSTP as generic actions or "groups of generic actions which, when combined, meet the objective of military tasks" [170a:I-12].

These functions represent "building blocks" that allow tasks to be broken down and considered in terms of smaller units, which can ultimately be quantitatively measured. Six separate functions are selected which apply to the space task list. These are: surveillance, communications, navigation, environmental monitoring, force applications, and space operations. Surveillance, force applications, and space operations are further broken down, resulting in a list of 15 functional building blocks which define tasks (see Appendix C). The MSSTP adds the qualifier that this list of functions is not comprehensive due to the "total number involved and because the selection will vary with the perspective of the individual" compiling the list [170a:I-12].

Each task is evaluated with respect to the 15 functions, and functions (those required to define the task performance and capability) are assigned to tasks. For example, the task "warning of ballistic missile attack on CONUS" has three functions associated with it: ballistic missile detection and track, space vehicle detection and track (both sub-categories under the functional heading of surveillance), and communications. Functions are described in sufficient detail to drive out performance needs for the task. For example, the function "ballistic missile detection and track" is defined as "detect the launch, track and identify all ballistic missile flights" [170b:5-3].

Derivation of Performance Parameters. Finally, performance parameters are derived for each of the function-task pairs to provide quantitative measures, which then define performance requirements to accomplish the tasks. Six measures of performance are cited in Volume I to assist analysts in quantitatively describing functional requirements imposed by the tasks. These are [170b:4-19]:

Coverage: Geographical boundaries over which the functions must be performed.

Capacity: The number of units served, detected, identified, tracked, etc. The number of messages, units, or bits transmitted or received per second.

Quality: Quantitative measures of the distinguishing attributes such as location accuracy, probability of detection, false alarm rate, probability of correct message receipt, track accuracy, probability of kill, etc.

Timeliness: Allowable system time delays or response times such as allowable time from event detection to message transmission of event detection.

Availability: Percentage of time the system must be in position and able to accomplish the assigned task.

Survivability: Endurance requirements imposed by the military mission or task. Specified in terms of duration (minutes, hours, days, years) a function must be available to accomplish the associated task.

Each function-task pair is evaluated with respect to these performance parameters in conjunction with six levels of the conflict spectrum: peace, crisis, theater non-nuclear war, theater nuclear war, central nuclear phase, and central reconstitution phase. Matrices are developed that show conflict levels as columns and performance measures as

rows, allowing for 36 discrete inputs for performance requirements [170b:4-20].

These measures are intended to quantify the specific performance requirements of each function as they relate to the list of military tasks that can be performed in space. If tasks are sufficiently described to define specific functional requirements, then performance parameters can be defined which then provide these quantitative measures. The quantitative measures in turn can describe the levels of technology required to ultimately perform the tasks. It is significant to note that performance parameters have not been specified for many of the function-task pairs addressed in Volume I.

Summary of Volume I. The methodology described in Volume I is designed to identify performance needs for system concepts. First, tasks pertaining to military requirements that can potentially be accomplished in space are derived from various sources. Space Division analysts review current guidance relating to military applications in space as expressed in policy and doctrine. They also consider U.S. capabilities, projected threats, and future operational requirements as defined in various needs statements prepared by operational users. Twenty-six possible tasks that can be accomplished in space are derived.

Next, these tasks are evaluated against a comprehensive mission list to validate their adequacy in terms of covering all space related mission requirements of the three

services. Then, fifteen military functions that can be performed in space are derived and analyzed to determine which ones apply to the twenty-six tasks. These functions are "building blocks" and serve to quantitatively describe specific task requirements. Finally, each function is analyzed in terms of six performance parameters which identify quantifiable needs imposed by the related tasks.

These needs are the basic output of Volume I and can be used to determine the capabilities space systems must have. In fact, these performance needs become the basic building blocks for the system designer when devising space-based concepts that can perform military tasks in space [170b:6-1].

Volume II, "System Concept Options". Volume II describes several system concepts that can be linked to the military tasks and performance needs addressed in Volume I. The early version of the MSSTP states that these concepts "are fabricated on the basis of the performance needs of Volume I" and may address a single function of a particular task or meet performance needs of a function that is applicable to several tasks. Alternatively, a system designer may devise several designs that perform the same function for a specific task to determine technology needs for these competing options [170b:6-1]. The interface that is intended to exist between Volumes I and II is depicted in figure 3-3 [170b:6-2].

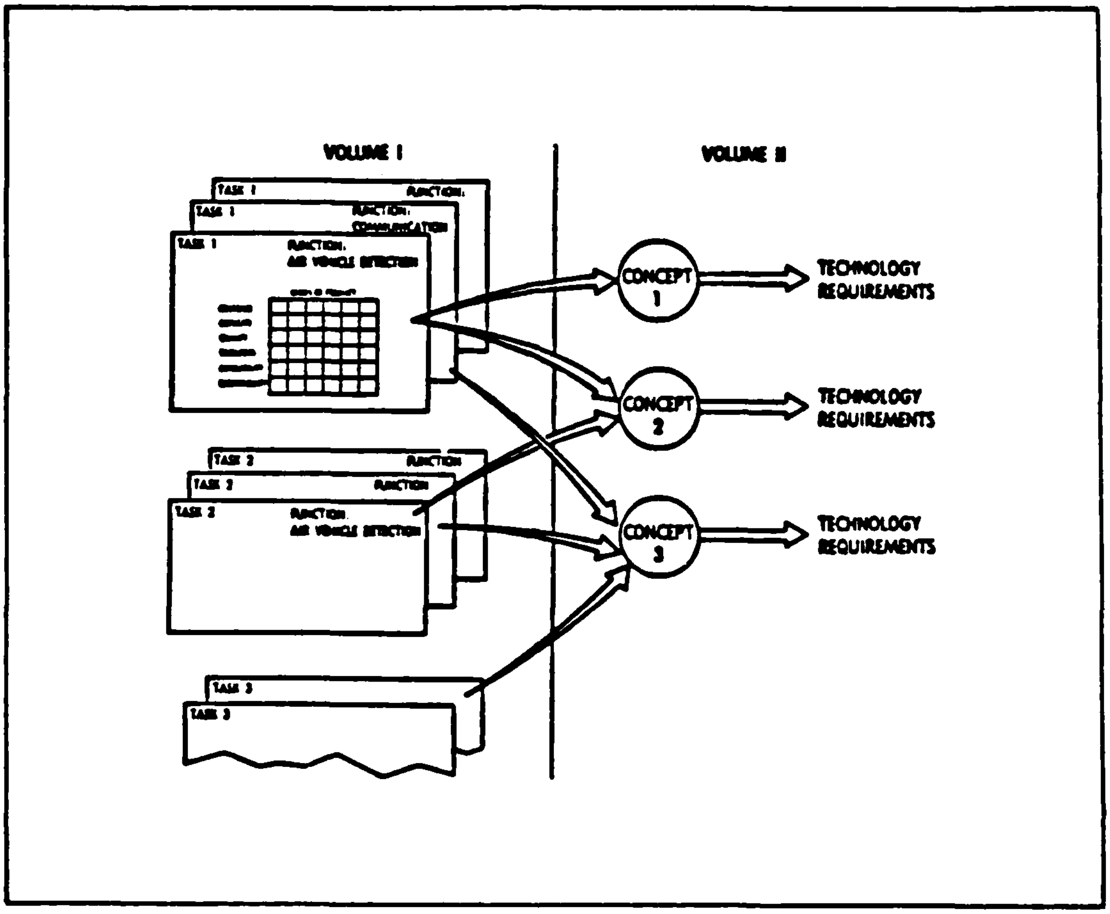

Figure 3-3. Vol I - Vol II Interface

The original Volume II listed 34 system concept candidates. Updates and changes in direction have changed this list considerably. Concepts are separated into three categories: near-term, far-term, and SDI (Strategic Defense Initiatives). Near-term concepts are 11 concepts rank-ordered by the Space Systems Architecture Study Group (SSA) in early 1984. They considered many of the original 34 concepts and others, and applied resource constraints in selecting the top concepts based on importance and IOC dates

(those with early IOC dates usually were considered higher priority than longer termed concepts). The second group, far-term concepts, includes those concepts not rank-ordered by the SSA, as well as concepts generated by STC, the Aerospace Corporation, and AIAA technology panels. These later concepts addressed known or projected deficiencies not covered by the SSA concept list. For example, heavy lift launch vehicle and orbital transfer vehicle concepts were included to provide a capability to lift the more massive payloads required by some of the SSA and SDI concepts into final orbits. SDI concepts are those concepts that directly relate to the Strategic Defense Initiatives recommended by the Fletcher Committee and alluded to during President Reagan's now famous ballistic missile defense ("Star Wars") speech [47; 253].

The intent of Volume II is to identify advances in technology required to make possible improved military space systems for the future. Concepts in Volume II are described in detail and include the technologies needed to build them. Projected IOC dates are associated with each concept. The assumption is made that required technologies must be available at least five years prior to the concept IOC date to ensure low-risk engineering development of the technologies. More than one concept may relate to the same military function/performance need, but will vary in terms of performance, risk, availability date, or technology requirements. Concepts are linked to the military tasks identified in

Volume I [170a:II-5]. Appendix D shows this linkage.

Originally, Volume II showed technology issue impacts on concept realization, where a technology issue represents a shortfall in performance that could not be met by existing or projected technological advances. These assessments were made by concept originators or long-range planners, who were often unaware of or qualified to make these assessments. Future editions of the MSSTP will list technology issues as an appendix to Volume II [144].

Concepts are not intended to be point designs for development. Instead, they represent a range of systems which could be developed by the year 2000 and are intended as "strawman" concepts to cover the "spectrum of anticipated future mission needs, to indicate levels of performance that are desirable and possible, and to serve as a basis for the planning of future developments in technology" [170c:II-1]. Concepts in Volume II provide the forum to identify technology issues that must be resolved in order to build the concepts or provide the capabilities called for by the concepts.

<u>Volume III, "Technology Trends and Forecasts</u>. Volume III is actually a two volume set that represents an extensive compilation of the current and forecasted state-of-the-art (SOA) of technologies required to support the space systems discussed in Volume II. The primary objective of Volume III is to present useful data for forecasting technologies relevant to future military systems in space

[170a:III-3]. Appendix E lists several of these technologies by technology discipline.

Within each technology discipline, specific information relating to current technology status, programs already underway or conceived (funded and unfunded) to advance the SOA of the technology, and forecasts for potential breakthroughs or upper bounds on the technology are documented. Where possible, figures of merit are defined and characteristics are described for each technology area. For example, under "Telescopes and Optics," performance figures of merit include: resolution, modulation transfer function, optical transmission over passband, out of field rejection, RMS wavefront quality, and energy on a detector element. Among the characteristics described for telescopes and optics are: focal length, field of view, aperture, spectral bandpass, weight, and temperature tolerance [170d:101]. Figures of merit are used to plot SOA and projected SOA against time to forecast technology trends. Known technology programs that are on-going or planned are also plotted to represent specific technology goals.

The output of Volume III is a forecast of the probable status of technology issues in the future. Many of the programs cited in Volume III are unfunded. The result is that many technology issues may go unresolved unless critical efforts are planned, funded, and initiated promptly.

<u>Volume IV, "Technology Assessments"</u>. In Volume II technology requirements are identified for each concept and

then compared with technology trends and forecasts discussed in Volume III to arrive at the assessments detailed in Volume IV. A shortfall between the projected technology available five years prior to a concept's IOC date and the required performance capability of the concept defines a technology issue. Technology issues exist when forecast technological advances are insufficient to provide the needed performance required by the concept.

Volume IV identifies technology issues based on the analysis described above and then summarizes the status of concepts with respect to the number and level of technology issues associated with each one. As you might expect, most of the concepts listed have at least some suspected technological deficiencies (gaps between projected SOA and performance required).

Significantly, Volume IV does not address systems trade studies, intertechnology trade-offs, or detailed design studies that potentially eliminate some of the technology issues [170e:iii]. Instead, Volume IV identifies those issues that appear most critical in ensuring the success of the concepts addressed in Volume II. Trade-offs and detailed design studies are the responsibility of the system designer. The MSSTP provides the information base to assist him in better defining the technology efforts required for development of a system.

Volume IV concludes with a list of "high-payoff" technologies which represent a qualitative assessment of

potentially critical technology issues. These technologies were subjectively identified by "implication, indication, and identification of technology gaps or deficits ('projected to be available') or by knowledge of apparent, but not indicated technology problems" [170e:189]. Appendix F provides a partial list of these high-payoff technologies.

Volume V, "Technology Plans". Since we were unable to review a copy of the published or current draft version of Volume V, our comments are based on the overview included in the Executive Summary and our recent discussions with STC personnel. Part of the reason for this incomplete review is that Volume V, as well as Volume VI, have gone through numerous iterations and changes. As discussed in the Executive Summary to the MSSTP, Volume V should present an unconstrained set of technology plans organized under the various technology disciplines introduced in Volume III. Technology programs would be conceived and documented to resolve the technology issues identified in Volume IV. Under each technology discipline the following information was to be included: a hierarchy of performance parameters for the technology; ongoing programs which lead toward attainment of these parameters; probabilities of success for each technology program, expressed as risk functions of time and funding; and logical extensions of the programs to resolve technology issues not specifically addressed by existing programs [170a:IV-3]. Also to be documented were the cost and schedule information for each technology

program and identification of participating organizations.

Based on our discussions, it appears that the current emphasis will be on technology issues as opposed to planning specific technology programs to resolve those issues. Responsibility for developing the detailed R&D programs will remain with the appropriate laboratories [229; 230].

Volume VI, "Technology Program". As we indicated in the introduction, Volume VI was to present the resource constrained technology plan. Technology programs discussed in Volume V were to be prioritized according to the technology issue weights with which they were associated. The weighting of technology issues was to be a function of the concept priority to which the technology issue was linked, the frequency of the technology issue (linkage to more than one concept or function-task pair), the relative weightings of missions supported by concepts, and other variables such as cost, timing, and availability. The prioritization process would identify a list of high priority technology programs constrained by available resources [170a:IV-9; 228].

Since the publication of the Executive Summary, Volume VI has gone through numerous iterations. For the near term, it appears that the published version of Volume VI will be limited to a condensed prioritized list of technology issues related to the three groupings of concepts discussed earlier (SSA, far-term, and SDI concepts). This listing probably will not reflect resource constraints [230]. The next

section describes TRUMP, the resource allocation model designed to make use of the information in the MSSTP.

<u>TRUMP (Technology Resource Utility Management Process)</u>. As we indicated in the introduction, TRUMP was a set of decision rules that was to use information from the MSSTP database and provide the STC with an "optimum" technology investment plan. It was a logical, straightforward methodology that failed to gain acceptance the first time it was applied to a real world situation [228]. To understand why it was abandoned as the method of choice for prioritizing technology programs and concepts, it is first necessary to understand how the process was designed to operate and the data requirements. The following discussion is based on interviews with Mr. Tim Spinney, the primary developer of TRUMP [242], and Lieutenant Colonel Pete Soliz [228].

<u>TRUMP Data Base Structure and Algorithm</u>. First of all, TRUMP was a combination of several entities. It depended on a hierarchically structured database and used an intelligent operating system, consisting of fairly user friendly commands, to sort and search through the database. It incorporated several "pre-processing" steps designed to further sort concepts and/or technology programs according to specified criteria. Finally, it included some simple mathematical algorithms designed to optimize technology programs and concepts on the basis of frequency, concept importance, risk, and cost (budget constraints).

The TRUMP database was organized as shown in Figure 3-4

[242]. Inputs for "area", "arena", "mission", and "mission requirements" came from Volume I. Note that "missions" correspond to the 26 tasks and "mission requirements" to the 15 military functions derived in Volume I. Concepts were input from Volume II, technology issues from Volume IV, and technology programs from Volume V.

Areas and arenas were weighted by relative importance according to mission area analyses performed by the Air Staff (recall tasks were prioritized in the Air Force Planning Guide). Areas and arenas directly corresponded to the DoD mission headings developed by the Under Secretary of Defense for Research and Engineering and used to relate military tasks to missions in Volume I of the MSSTP. Areas were either Strategic or Tactical Warfare, and arenas represented broad divisions of responsibility under areas. For example, "offense" and "defense" were arenas under Strategic Warfare, while "air", "land", and "sea" represented arenas under Tactical Warfare.

Weightings were "normalized" so that total weights horizontally (across the levels under a single higher element) summed to 1.0. In other words, if there were two areas (strategic and tactical), the sum of their weights had to equal 1.0. These weights were defined as the "utility" of the given area or arena. Task ("mission") priorities were obtained by multiplying the weights of the "arena" and "areas" to which they were linked.

TRUMP used the utilities derived by the Air Staff for

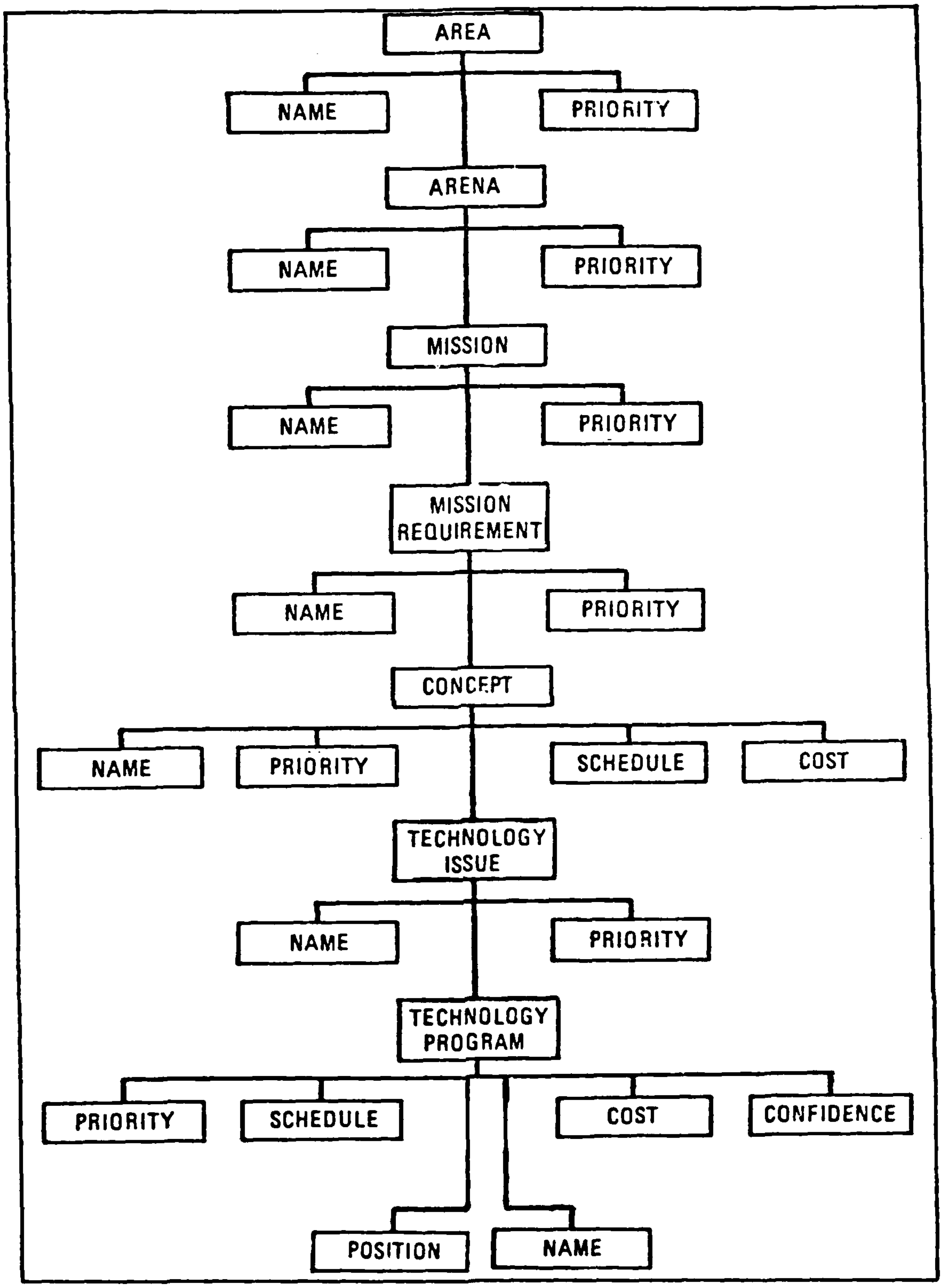

Figure 3-4. TRUMP Database Organization

"missions" to determine weights for "military requirements", "concepts", and "technology programs". Functions ("military requirements") were prioritized by considering the number of times a particular function appeared under a given area (through linkage with "missions") and then multiplying this integer value times the weight of the "missions" associated with this arena. The total utility of a function was found by summing these products for every applicable arena. For example, if communications (one of the 15 functions identified in Volume I) supported 3 missions under arena A (with utility = Ø.36) and 2 missions under arena B (with utility = Ø.42) and no others, then the total utility for communications would be: (3)(.36) + (2)(.42) = 1.92.

Concepts supporting the "mission requirements" were similarly prioritized. The utility of a concept supporting a single mission requirement was simply the utility of the associated mission requirement. The utility of a concept supporting more than one mission requirement was a function of the frequency and the relative weights of the mission requirements under which it appeared. Utility values for concepts were derived as described above for mission requirements. TRUMP then applied budgetary constraints to the concepts, and output two sets -- a prioritized funded concept list and a prioritized unfunded concept list.

Utilities for technology issues and technology programs were similarly calculated. A technology issue was defined in TRUMP by the set of technology programs that related to

an unresolved technology problem that prevented development of the associated concept using known or projected SOA technology. Neither technology issues nor technology programs were necessarily "collectively exhaustive" or "mutually exclusive." In other words, the technology issues linked to a concept did not necessarily represent all technology issues whose successful resolution was necessary to build the concept. Others may exist that are undefined or unknown. Likewise, resolution of one technology issue may resolve all or part of another technology issue related to the concept.

The same can be said of technology programs. Additionally, technology programs could be subordinate to one another. For example, the success of a technology program could depend on the success of one or more subordinate programs.

Technology program data requirements included: the name of the program, its priority, schedule, cost, confidence (a subjective estimate of the probability of success), and position (is it subordinate to other programs). This information was extracted from Volume V of the MSSTP. Data relating cost, schedule, and risk (1 - confidence) were maintained in the database on each technology program in a 3 x 3 matrix format. Each technology program matrix had nine input values. The center point, called the nominal value, was set at Ø.8 and represented the confidence level (estimated probability of success) of completing the particular

program at a set funding and schedule level. The remaining eight points were reserved for confidence values for various combinations of schedule and cost. Schedule (time) was plotted on the ordinate, with intervals of ± 20%. Likewise, cost was plotted along the abscissa, with the left side representing a 20% reduction in budget and the right side a 20% increase. For example, the top lefthand corner of each technology program matrix would show the estimated confidence that a particular technology program would succeed if the budget were cut 20% and the schedule reduced by 20%.

So far we have discussed how TRUMP prioritized concepts, technology issues, and technology programs. We saw how the database included quantitative information on each technology program relating to cost, schedule, risk (as a function of the probability of success or confidence), and the number of subordinate programs. Additionally, Volume II of the MSSTP provided concept IOC dates, which in turn define technology required availability dates (five years prior to IOC). These data are used by TRUMP in several preprocessing steps to generate an "optimal" prioritized technology program list subject to budgetary constraints by matching related technology programs to the prioritized concept lists (funded and unfunded) previously discussed.

Given an acceptable risk level for technology programs and a budget limitation provided by higher headquarters, TRUMP would first process technology programs associated with the top priority concept. If all technology programs

could be accomplished by the projected IOC date of the concept at or above an acceptable risk level, the technology program with the least cost was selected to support that particular concept (by resolving the technology issue the program was linked to). Otherwise, the algorithm identified the concept as supportable (can be accomplished by IOC date but at an unacceptable risk) or as late (none of the technology programs can be completed in time to meet the concept IOC date, regardless of risk or cost). Technology programs were then matched to the respective concepts they supported, according to concept priority. This procedure continued until budget constraints were satisfied.

Problems With TRUMP. TRUMP was abandoned as the methodology for prioritizing technology programs when the Space Systems Architecture Study Group attempted to use it to prioritize concepts earlier this year. Group members were not satisfied with the prioritized list generated by TRUMP. A major reason for their dissatisfaction with the technique was that group members did not fully understand the process and had no part in determining utilities of mission requirements. Their major consideration was projected IOC dates of concepts, and they ultimately prioritized concepts primarily on the basis of IOCs (those with the earliest IOCs generally received high priorities) [228].

TRUMP had other problems as well, many due to the fact that it represented a first attemp at a quantitative approach to optimizing a prioritized list of technology pro-

grams. Some of these problems are discussed below.

Recall that confidence levels were assigned to each technology program as a function of time and funding (the nominal value being 0.8). Technology programs could be subordinate to other technology programs. If TRUMP found one technology program dependent on the success of more than one other technology program, the value for the lowest estimated probability of success was assigned to the top program. Accepted probability theory dictates that if an event is dependent on more than one other event occurring, then its probability of occurring is the product of the probabilities of all other events it is dependent upon. The following example illustrates the point.

Assume a technology program is dependent upon the success of two other programs (A & B), as shown in Figure 3-5. Furthermore, assume technology program A can be resolved by <u>either</u> technology program A1 or A2, while technology program B depends upon successful completion of <u>both</u> subordinate programs B1 and B2. Finally, assume all programs are at their nominal values (probability of success is 0.8). TRUMP would show that the final probability of success or confidence of the technology program is 0.8 (the lowest of any of the subordinate programs). Application of probability theory would show different results, with the probability of success of the top program dependent on the success of subordinate programs A <u>and</u> B. The probability of success for program A is 0.96 [1-(0.2)(0.2)], while the

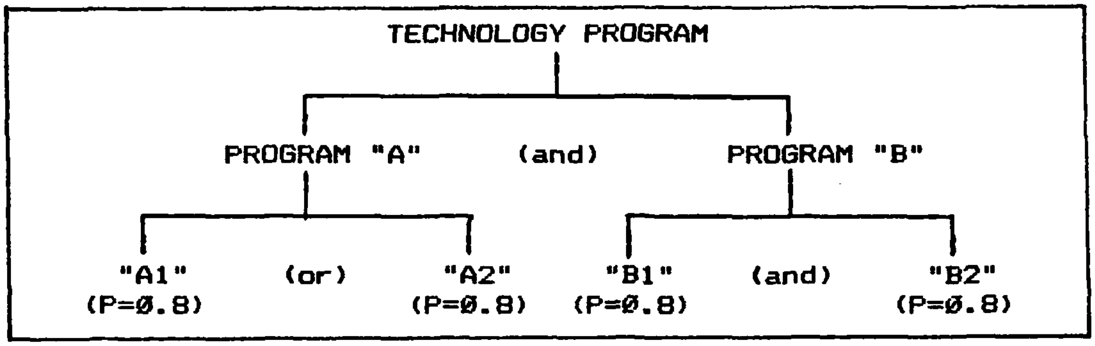

Figure 3-5. Derivation of Probability of Success

probability of success for program B is 0.64 [(0.8)(0.8)]. Since the top program depends upon both A and B being successful, its probability of success is the product of the probabilities of A and B, or (0.96)(0.64) = 0.6144, significantly less than the TRUMP value of 0.8!

Another problem is the manner in which probabilities are elicited. Laboratory personnel and AIAA technology panel members were asked to estimate the amount of funding and time necessary to ensure a confidence level of 0.8 (the nominal value) for each technology program. Then they were asked to estimate probabilities for the other eight elements of the 3 x 3 matrix to determine confidences if funding and time were reduced or increased in 20% increments. These estimates were made on the basis of "best guesses" with little or no known information. In one lab, methods for estimating these values varied from time consuming discussions with other experts to obtain consensus to lab personnel quickly filling in the matrix values and "gaming" the system (i.e., reflecting extremely low values for fun-

ding and time reductions and slightly higher probabilities than the nominal value for increased funding and schedule) [122].

We have already pointed out in Chapter Two the inherent problems with making subjective estimates in an environment of uncertainty when we discussed eliciting subjective probabilities. Furthermore, we believe data provided on the probabilities for the ± 20% increments of time and funding to be unrealistic, considering the variance in methods used to solicit data and the large amount of uncertainty. For example, Rowe and Somers point out that in a survey of 47 major programs, interim estimates averaged 218% <u>over</u> initial estimates [192:19]. These figures indicate that attempting to estimate probabilities for increments of ± 20%, when the initial estimates for costs and funding are likely to be off by better than 200%, will not provide meaningful information and should not be used as inputs in a quantitative model.

The points made above highlight one of the major detractors of TRUMP. Despite the fact that it incorporated subjective probabilities, the final output for all intents and purposes could be interpreted as deterministic. The methodology was designed to provide a prioritized list of technology issues subject to budgetary and time constraints. If funding the least expensive technology program of several possible candidates would satisfy a given technology issue (assuming risk and time constraints were met), then only that program was selected. Recall that TRUMP worked to

satisfy technology issues relating to concepts (i.e. resolve all technology issues related to the top priority concept first, assuming time and risk constraints could be met). Consider the following example.

Assume all technology issues associated with a top priority concept could be resolved by single programs at nominal levels (P[Success]=0.8). Further, assume risk levels were at or below 0.2 (1-P[Success]) and that time constraints (technology issues resolved five years prior to concept IOC date) were met. The TRUMP methodology would conclude that all technology issues related to that concept could be resolved at a cost that equalled the summation of the costs for the technology programs selected, with a probability of success of 0.8. We have already pointed out that TRUMP ignored the dependency axioms of probability theory. In fact, the probability of success for resolving all technology issues associated with a given concept would equal the product of the probabilities of success for each technology issue, a significantly smaller value than 0.8.

Furthermore, the literature supports the premise that success in R&D is maximized by the number of independent programs undertaken to resolve a particular technology problem. For example, Peters and Waterman [185] point out that parallel projects are crucial to the success of an R&D effort. They cite an IBM executive who stated that in every major successful development project "there were two or three (about five once) other small projects, ... (comprised

of) four-to-six-person groups, ... who had been working on parallel technology or parallel development efforts" [185:205]. Many other authors similarly conclude that an organization's chances of successfully resolving technology problems are improved by, among other things, maximizing the number of independent and parallel efforts [21; 26; 41; 100; 101; 179; 187; 240; 241].

Along the same lines, the literature (and many of the people we interviewed) conclude that most R&D efforts never deliver as promised. In most cases, success is measured by some percentage of the originally stated performance objectives for the research effort. For example, one STC technologist related that during the time he worked with the Advanced Manned Spacecraft Concept, most of the contracted research and development efforts resulted in some reduced performance capability than the initially contracted for performance. He further stated that parallel efforts, when they could be afforded, usually provided system designers with enough technology tradeoffs to provide the required capability [132]. Other authors also support the premise that combining the results of parallel R&D efforts often provide the necessary performance required, where no single project could [41; 185; 187].

In summary, TRUMP was an attempt to solve the difficult problem of quantitatively optimizing a resource constrained list of technology programs. Through sophisticated algorithms and sort techniques it took subjective data and

output lists of funded and unfunded technology programs that would resolve technology issues crucial to the success of concepts. We described some of the problems with TRUMP. These included a decision methodology that did not allow for inputs from the decision maker (weighting of concepts, technology issues). Also, TRUMP treated highly subjective (and uncertain) data in a deterministic manner. Moreover, this discussion pointed out some of the considerable difficulties in attempting to quantify R&D advocacy, which must operate in an environment of great uncertainty. The next section addresses how STC has attempted to prioritize technology issues in the absence of a quantitative model like TRUMP.

STC Implementation of MSSTP

With the *abandonment* of TRUMP, the Space Technology Center had no methodology for prioritizing technology issues. Faced with compressed suspenses to publish Volume VI, the prioritized technology issue list, STC developed a qualitative methodology for rank ordering technology issues in terms of their relative importance to concept realization. We had the opportunity to observe application of the process while on a visit to STC in June 1984. Comments made in this section are, for the most part, based on our personal observations and subsequent discussions with STC personnel.

The technique adopted by the STC was designed to prioritize technology issues as they related to the three groups

of concepts previously described in our discussion of the MSSTP -- SSA (near-term), far-term, and SDI concepts. SSA concepts were prioritized with respect to each other based on an ordinal scale. That is, concepts were ranked with respect to the other concepts in the SSA group, but the differences between the numbers had only relative and not absolute meaning. The far-term concepts were ranked using SSA mission weights derived through mission area analysis. SDI concepts were not ranked.

Technology issues under <u>each</u> concept were weighted with respect to their importance to the concept using what was intended to be an interval scale from 1 to 5. The highest weight ("5") was to be assigned to those technology issues that were enabling, i.e. the concept could not be built without resolving the technology issue. The lowest weight ("1") was reserved for those technology issues which were only beneficial to the concept (resolution of the technology issue may contribute to the performance capability of the concept, but was not crucial to its success). Integer values between 5 and 1 were assigned to technology issues based on the following criteria: "5", representing a technology issue which would cause a concept degradation of 80 to 100%; "4", 60 to 80% degradation; "3", 40 to 60% degradation; "2", 20 to 40% degradation; and finally, "1", 0 to 20% degradation. We note here that there was no intent to rank-order technology issues within a given concept (if all technology issues were considered enabling to the concept,

then all could potentially receive the highest weighting of "5").

After each technology issue was weighted within each of the concepts, then the ranking of the concept (where applicable) and the frequency of occurrence of the same technology issue appeared with respect to the concepts were considered. Various algorithms were suggested to ultimately prioritize technology issues within each of the three groups of concepts, taking the above three factors into account. As of this writing, none of the methods have been accepted. For the most part, this is because the methods suggested thusfar have mixed ordinal and cardinal numbers in mathematical operations [23]. For example, one method multiplied the concept weight (an ordinal number) with the technology issue weight (intended to be a cardinal number) and the frequency (a cardinal number) to determine the overall weight of the technology issue with respect to other technology issues within the SSA concept grouping. Recall that ordinal rankings do not reflect absolute values between each of the ranked elements. For this mathematical operation to make any sense, the ranking between concepts must be based on an interval scale as a minimum, which would provide the information "how much more important is one concept with respect to another."

Despite the fact that an accepted methodology for justifying a final prioritized technology issue list has not yet been found, understanding the process used by the STC to

weight the various technology issues is useful. A group of technologists, representing various technology disciplines, was formed to evaluate technology issues as they related to a list of 28 concepts. Concept packages were provided each group member, where each package contained the concept title and the technology issues related to it. Technology issues were organized under each of the 17 technology disciplines addressed in Volume III of the MSSTP.

Group members devoted one hour to each of the concepts. An expert familiar with the concept had 15 minutes to brief the group on the concept description and an additional 15 minutes to describe the technology issues associated with that concept. Another 15 minute period was dedicated for discussion of the technology issues, where group members could query the briefer for information about the concept or the associated technology issues. Finally, 15 minutes was reserved for group members to vote on the technology issues, assigning each issue a value from 1 to 5 based on the importance of the technology issue to the concept. Except for the "interval" scale description provided earlier, there were no other attributes defined for this scale.

The ultimate objective of the process was to surface enabling technologies ("5" rankings) associated with the concepts. Group members considered points made during the concept discussion and their own expertise in ranking technology issues as "high" (5), "medium" (3), or "low" (1), with the integers 2 and 4 reserved for in-between ratings.

Individual voting results were tabulated and averaged with the results from other group members to arrive at average weights assigned each of the technology issues. Then these average weights were considered with respect to concept priority and frequency to determine an overall prioritized technology issue list for each of the concept groupings.

We were present for two and a half days of the voting process. During this time we had the opportunity to observe the group interaction and the questions and concerns group members raised about the process and the information briefed. These observations and the tentative conclusions we drew from them are discussed in the next several paragraphs. They are pertinent to this thesis effort since they helped identify for us valid concerns that must be addressed in any methodology which qualitatively describes attributes used as performance measures to rank order elements.

The discussion below is by no means complete. However, we attempted to filter the important factors that seemed to have had the greatest impact on the ranking process. They also add background information for the discussion that follows in the next section.

First of all, concept packages were sometimes inaccurate or incomplete. For example, the same technology issues sometimes were duplicated under different technology disciplines for a given concept. This confusion among voting members had to be resolved during the one hour time period reserved for discussion of the concept. Concept briefings

varied in completeness. Some were more detailed than others. In some cases, briefers assigned for particular concepts were not fully knowledgeable of all the details or objectives of the concept. In other cases, too many technology issues were identified for a given concept to be adequately addressed in the one hour time frame allotted. At least four (that we know of) concepts had over 125 technology issues related to each one. These factors can only adversely influence the identification and ranking of critical technology issues associated with particular concepts.

Another problem was that there did not appear to be a consistent definition for "technology issues" among group members. Recall that the MSSTP defined a technology issue as the difference between the projected technology SOA five years prior to the IOC of a given concept and the capability required by the concept. However, some considered a technology issue to be any technology capability required to build the concept, whether the technology was projected state-of-the-art or not. Others felt that one technology issue should be selected among those potentially able to resolve similar deficiencies. For example, man-in-space issues were dropped in some cases because group members felt autonomy technology issues would resolve the on-orbit maintenance, operations, and station-keeping technology issues. The confusion caused by the inconsistency in definitions resulted in group members making trade-offs between technologies, prioritizing issues that did not fit the MSSTP defi-

nition of a technology issue, and deleting some technology issues from consideration. These problems could be rectified by ensuring group members understood and accepted the working definition of technology issues before applying the process.

We also observed that the concept to technology linkage did not necessarily identify all pertinent technology issues. The purpose of the concepts, as stated in the MSSTP, was to identify technology issues related to building space systems in the future. They were not intended to be "point designs." Nonetheless, we found that group members seemed to focus on concepts as point designs. They traded-off technologies against each other (as we pointed out in the man-in-space vs. autonomy example); deleted some technology issues; or failed to add others that potentially supported concept deployment, employment, or sustainability. Additionally, group members often questioned the extent to which concepts supported the military tasks to which they were linked. As we mentioned in the last section, this information is not available in the MSSTP.

Finally, various biases surfaced during the process. As we mentioned earlier, the level of expertise among briefers varied, as did presentation formats, styles, and detail of information presented. Furthermore, while the group composition was appropriate for prioritizing technology issues within concepts, it did require the experts to evaluate technology issues outside of their areas of exper-

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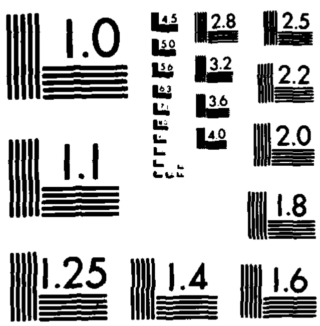


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

tise. Group members were particularly dependent on the briefer and his presentation for pertinent information. As discussed by Hogarth and Makridakis [120], individual and group biases can adversely affect these processes.

On the other hand, if all technology issues had been grouped by discipline, and criteria identified to prioritize issues within disciplinary areas, then technology experts having the expertise in the particular discipline could be selected to prioritize these issues. This procedure would have eliminated trade-offs occuring between technologies, the deletion of certain technology issues, and the uncertainty felt by some group members when evaluating technologies with which they were unfamiliar. It certainly would not eliminate all biases, but it would limit the number of different biases and facilitate identifying the presence and effect of other biases [120; 53].

Up to this point we have presented an overview of the MSSTP process by describing the methodology and various attempts to apply the methodology. The MSSTP has significantly contributed to the body of knowledge by providing a comprehensive database of space-related R&D efforts and requirements. Air Force organizations and the aerospace industry have found this information useful when considering or presenting design proposals [230]. However, the MSSTP has limitations in its methodology. Many of these are simply due to the dynamic nature of the process and the environment in which it operates. In the next section we

analyze the MSSTP process and summarize its major limitations.

Analysis of the MSSTP

In our discussion of the MSSTP we learned that one of its objectives was to identify space technology issues that support space system architecture options over the next two to three decades. The technology plan was to be derived through quantitative analysis. Information available in the MSSTP database was manipulated within a mission area analysis framework to identify an "optimum" list of prioritized technology programs. Using information previously presented as background, we analyze the MSSTP's utility as a methodology for technology planning to provide the broad technology base to support the space system architecture of the future.

Utility of Quantitative Approaches to the R&D Advocacy Problem. We have shown that the MSSTP process is heavily dependent on subjective data. Technology issues are prioritized using qualitative attributes and linkages to concepts. Performance parameters are designed to be quantitative goals for concepts, and yet are qualitatively derived by projecting threats and future required capabilities. Specific data describing technology issues and programs discussed in Volume V of the MSSTP are similarly derived. Estimates for costs, timeframes, and program risks are "best guesses" provided by laboratories and AIAA panels. All of these data are generated in an environment of uncertainty and yet the

thrust of the MSSTP is to use these subjective data as "deterministic" or "point estimate" values in defining a final space technology plan.

We pointed out in Chapter Two the uncertainty inherent in the R&D process. The process is subject to unforeseen changes in funding, policies, and leadership support, which themselves are influenced by a variety of other external factors. Each R&D program is unique. No realistic method exists for applying experience or historical data from previous R&D programs to predict trends or forecasts for future R&D efforts. Most other management science applications (inventory control, transportation algorithms, linear/stochastic programming, etc.) either are deterministic (all input values are known with certainty) or probabilistic (input values can be predicted on the basis of known probability functions for input parameters). R&D portfolio selection models on the other hand must rely on uncertain data, where even the probability functions of input parameters are unknown.

We also discussed how most quantitative decision models dealing with R&D portfolio selection problems attempted to deal with these uncertainties. Data were solicited from knowledgeable personnel (in the form of subjective probabilities) and used as inputs to probabilistic or deterministic models to output "optimal" decisions. We pointed out that subjective probabilities are subject to numerous biases and tend to be highly inaccurate in forecasting future outcomes

(costs, timeframes, or probabilities of success for given programs). The impact of biases and uncertainty are magnified with the complexity of the problem. When inputs depend on numerous organizations with differing perceptions, goals, and values, the validity of the data as point estimates is even more suspect.

Recall from our discussion of Volume I of the MSSTP that these factors played a significant role in deriving tasks and performance parameters. Additionally, qualitative attributes assigned to other MSSTP parameters are also questionable. For example, the MSSTP assigned qualitative attributes to timeframe (near-term, mid-term, and far-term), risk (low, moderate, and high), and effectiveness (highly and moderately). We queried STC experts on the validity of these attributes, since we were exploring the feasibility of using these values as inputs ourselves to develop a quantitative approach to the problem. We learned that STC has very little confidence in even the qualitative descriptions assigned to these parameters.

Reasons for this lack of confidence varied, but most of the difficulties stem from the fact that inputs for these parameters were provided by several different organizations, representing various interests and possessing different goals, values, and interests. For example, the attributes for timeframe implied different target dates to different organizations. Laboratories and industry considered "far-term" to mean "after the year 2000," which reflected their

R&D orientation (R&D efforts normally take years or decades to complete). On the other hand, SPOs (System Program Offices) work with actual systems (requiring R&D to upgrade capabilities in the near future) and consider "far-term" to represent the next "block change" (next system modification), which could occur in a few short years. Similar examples exist for risk and effectiveness [144].

The point is that a majority of the MSSTP inputs are qualitative in nature, highly subjective, and elicited in an uncertain environment. The net result is that outcomes from MSSTP based decisions cannot be predicted using deterministic or probabilistic methods. Unless approaches are adopted by STC to standardize methods for eliciting data, checking for consistency, and accounting for the subjectivity in the estimates, we believe that output from quantitative decision models will be ineffective in projecting or planning space R&D needs for the future.

<u>The MSSTP Methodology May Not Surface All Critical Technology Issues</u>. The methodology depends on several factors to identify critical space-related technology issues. These include: military tasks, performance parameters, consideration of technology trends and forecasts (projected SOA), and concepts. Due to the uncertainty associated with the process for deriving these factors, the technology issues surfaced by the process may not completely represent the critical issues that need to be resolved to meet future military space requirements.

Recall that technology needs for the future were to be identified by selecting tasks that represented potential space requirements of the future. Volume I of the MSSTP recognized that this task list could not be generated simply by extrapolating current tasks forward in time. Instead, projected threats were hypothesized and tasks necessary to meet these threats were defined. Performance parameters to accomplish each task were derived by focusing on the mission requirements to support each task and then evaluating these requirements in terms of quantitative figures of merit. Concepts linked to military requirements would ultimately define technology issues to be resolved to provide the capability to build future military space systems.

However, as we pointed out in our discussion of Volume I, there were problems with this task list. We noted that there was inconsistency in describing tasks, which was substantiated in discussions with STC personnel [144]. This resulted in some overlap of task descriptions, and overlap between tasks and missions. Even though threat projections (based on imperfect information) were used to extrapolate tasks into the future, tasks were still "filtered" through current policies and doctrine. Volume I cites doctrinal guidance as published in Air Force directives and national space policies as factors used to derive tasks. Additionally, while published doctrine reflects the philosophy that "space is a place" where military missions can be conducted, mission descriptions still reflect separate space missions

[6:2-6]. While these factors did not readily appear to be constraining, we noted during the prioritization process at STC that group members tended to consider policy and doctrine (as expressed by current military thinking) when evaluating concepts. For example, man-in-space issues were deleted as technology issues for one concept because group members felt that current military policy did not support a military manned presence in space.

Performance parameters were to provide quantitative measures of task requirements. They were derived by projecting future threats and capabilities for each task. As we have already discussed, projecting an adversary's capabilities and intentions for a future timeframe is an uncertain process. In our discussion of Volume I we also indicated some of the problems encountered in deriving performance parameters. The net result is that many of the tasks do not have performance measures specified for them, and where they are specified, they may be off by as much as an order of magnitude [144]. Since performance parameters were ultimately used to help identify requirements to be met by technology issues, incomplete or inaccurate performance levels could mean that all critical technology issues have not been identified.

Similarly, the working definition of projected state-of-the-art (SOA) technology could possibly result in some technology issues not being identified as such. Recall that technology issues were defined as the difference between

concept performance requirements and the projected SOA technology to support the requirements. If a technology was projected to provide the required capability five years prior to the concept IOC, then no technology issue was defined. However, technology projections are subject to large degrees of uncertainty. Volume III, which detailed technology trends and forecasts, lists certain projected capabilities that are projected to be available <u>only</u> if funded and initiated at given times and levels. Other projections are based on technology programs underway but not complete; or funded, but not yet initiated. There are no guarantees that these programs will deliver promised capabilities on time and at cost. In fact, the chances are they will not [192]. Obviously, if projected SOA fails to deliver the promised technology five years prior to concept IOC, then it should have been identified as a technology issue in the first place. We believe a more realistic approach is to define all technology shortfalls that cannot be met with current technology as technology issues.

We also note that the concept linkage used to identify technology issues does not address the extent to which concepts support task requirements. An obvious goal of deriving tasks to meet future requirements is to determine performance levels for these tasks. Assuming performance requirements are known with certainty (they are not), and that current technology will not provide the capability required, then the difference between current (and/or pro-

jected) capabilities and task performance requirements should identify technology deficiencies. Concepts are linked to tasks (through mission requirements/functions) to show that they in some way support task accomplishment. However, they do not identify the extent to which they support task requirements. It is possible then that in cases where concepts marginally contribute to task accomplishment, other technology deficiencies may exist and should therefore be identified and addressed.

The process also does not comprehensively identify the support architecture needed to deploy, employ, or sustain the concepts if they are built. These support issues are largely ignored except for some special cases (as is the case with the heavy lift vehicle and orbital transfer vehicle concepts). As a result, some critical technology issues may go undefined that are crucial to the successful employment of the concepts. This point was raised by various group members during the prioritization of technology issues last summer. Group members pointed out that some concepts called for large, space-based structures, and that the capability or "proven" technology for constructing large structures in space does not currently exist. Furthermore, there were no concepts that addressed these types of capabilities. The group guidelines, however, were to avoid consideration of support requirements.

Finally, the linkage to concepts is a two-edged sword in the technology advocacy process. STC's goal is to ensure

a broad technology base for the future which supports a wide range of options and potential space-based concepts [228]. From this perspective, it is best to divorce technology advocacy from direct linkage to concepts. However, by linking technology issues directly to concepts the possibility exists that STC may find itself involved in advocating specific concepts to ensure consideration for critical technology issues. Thus, the organization could find itself embroiled in the politics of advocating sensitive concepts and diverted from the goal of ensuring adequate support and funding for the technology issues and programs themselves.

Concept Linkage in the MSSTP Hierarchy. Consideration of these factors -- task and performance parameter derivation, projected SOA, and concept-linkage -- indicate that the chance exists that not all critical technology issues may be addressed. We believe that concepts are a useful mechanism for identifying technology issues, but others exist as well. We discuss these other approaches in Chapter Five. On the other hand, we think that concepts should be used only to identify potential technology issues, and not be linked back to military tasks as part of the technology issue prioritization process.

Both the MSSTP and TRUMP use a "mission needs" hierarchy to show linkages between missions, tasks, functions (mission requirements), technology issues, and technology programs. In the case of the MSSTP, we noted that the hierarchy is implicit (not actually diagramed), while with

TRUMP, it was explicit in the database organization. Both highlighted that tasks (missions in the TRUMP hierarchy) were weighted by the Air Staff using mission area analysis (assigning utility values based on the relative importance of the various elements). Although the MSSTP no longer attempts to prioritize concepts on the basis of mission area analysis, concepts are retained in the hierarchy, some by priorities assigned through other processes. This is to show linkage to military tasks, yet concept descriptions do not reflect the extent to which they support these tasks. We see no benefit in maintaining the linkage after technology issues have been identified.

On the other hand, linkage of technology issues to higher levels in the hierarchy should be maintained. If performance parameters can be better specified in terms of identifying projected task requirements, then they would represent excellent quantifiable technology goals. Technology issues could be linked to these goals and evaluated in quantifiable terms as to the degree of support they provide. We do not propose that such a methodology would necessarily work to identify all critical technology issues. Certainly some issues would surface simply by comparing differences in performance requirements and current or projected capabilities. However, other issues would not necessarily surface through such an analysis.

For example, assume a given surveillance requirement calls for 10 million infrared sensing elements to provide a

required resolution capability called for in a task. A technology issue could be easily defined to resolve the difference between current state of the art and the projected resolution requirement. However, other possible technology issues relating to heat dissipation, materials, or pointing and tracking problems necessary to put the sensing elements in operation may not be directly defined from this process.

The important point here is that retaining the linkage between concepts and tasks in the hierarchy after technology issues have been defined can be misleading. Since concepts do not show the extent to which they support task accomplishment, no meaningful conclusions can be inferred from the linkage, other than the concept supports the task to which it is connected to some degree. TRUMP did not make this distinction when prioritizing concepts on the basis of utilities assigned higher level elements to which concepts were connected. This may have been one more reason why it was ultimately abandoned as a methodology for optimizing a space technology plan.

Conclusion.

In this chapter we presented a brief overview of the MSSTP and TRUMP processes, and summarized STC attempts to implement the MSSTP. The last section provided a brief analysis of some of the limitations we found with the methodology. Our ultimate objective, as stated in Chapter

One, is to present a decision support structure for advocating space-related R&D issues. The emphasis in this chapter has been on the problems and limitations of the current methodology. Taking some of these concerns into account in our proposed structure, we hope to improve on the current process.

Using the background provided in this and earlier chapters, we describe the environment in which the space R&D advocacy process must operate in the next chapter. This description leads logically to an alternative hierarchical approach. We present this hierarchy in Chapter Five.

The MSSTP and TRUMP, both present a hierarchical approach to evaluating the R&D advocacy problem. The hierarchy is implicit in the MSSTP, with national policies, national security objectives, and doctrine discussed in the context of ultimately defining military tasks. While there was no direct connectivity shown between these elements and military mission areas, linkages to lower level elements were clearly defined. Although the TRUMP hierarchy was explicitly diagramed, it did not reflect linkages (assumed or otherwise) above mission areas. Both hierarchies have been combined in Figure 3-6. The hierarchy we present in Chapter Five completes the linkages between national needs and military missions.

The MSSTP used a hierarchical approach to show the linkages between military tasks and technology issues through concepts. In the process of deriving tasks, the

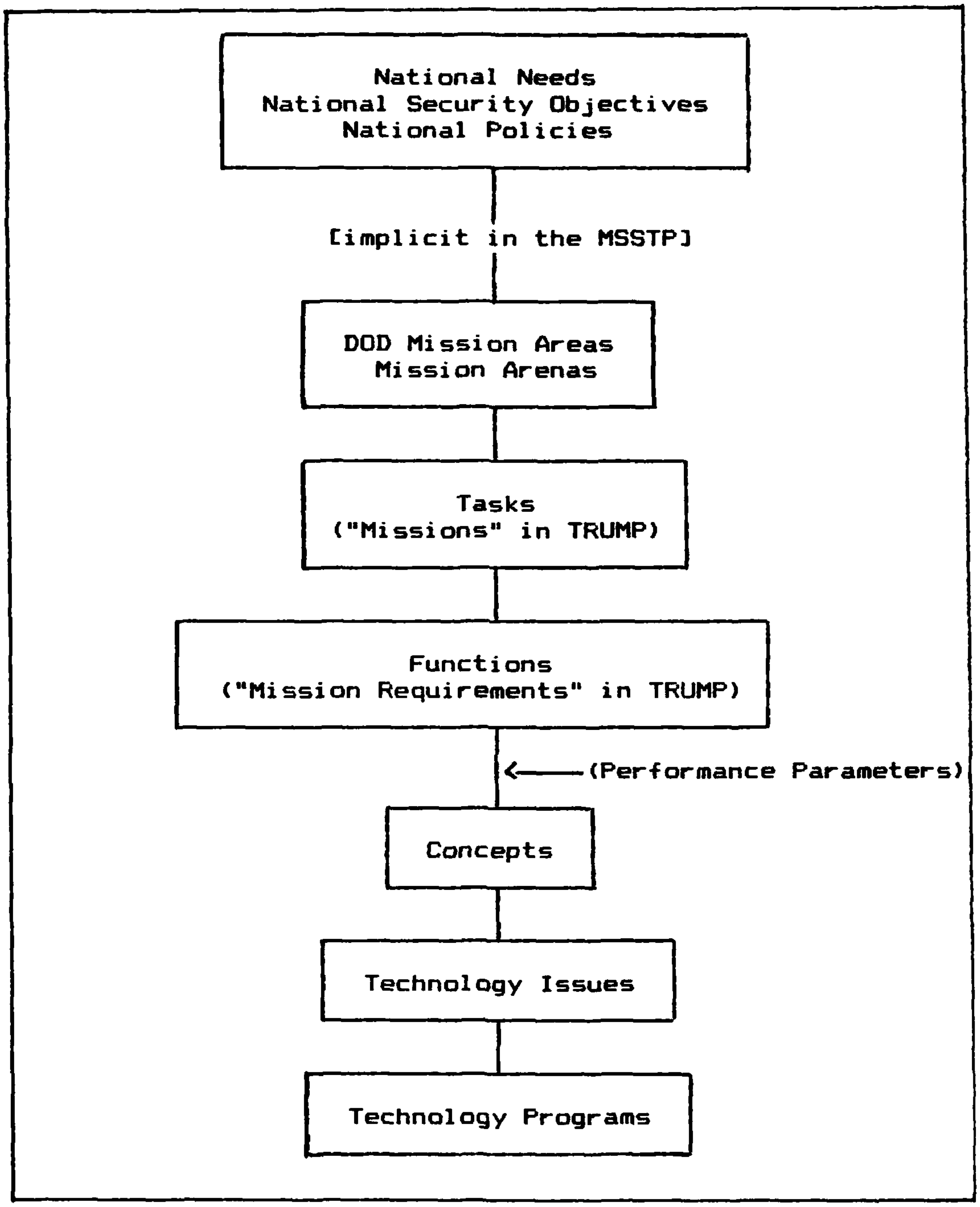


Figure 3-6. MSSTP "Mission Needs" Hierarchy

MSSTP considered the impact of policies and doctrine. While current doctrine indicates that space is part of the opera-

tional environment where military missions can be performed or supported, it still shows space as a separate mission category. This causes some confusion when linking space related missions to the DOD mission needs tree described in this chapter. For example, one of the specific responsibilities for space systems is to provide force enhancement to other mission areas. Thus, "ballistic missile accuracy enhancement" is defined as a task in the MSSTP. The hierarchy we present avoids this confusion by explicitly including consideration for "space as a place where military missions can be performed." Furthermore, we propose that policies and operational doctrine (what we will define as organizational doctrine) should not be as influential as they are in the MSSTP for identifying tasks and ultimately technology issues. We believe the minor modifications we recommend allow for greater flexibility when evaluating technology issues as they relate to projected operational requirements defined by the tasks.

Finally, we suggest additional linkages to national needs other than through the mission needs tree to address potential R&D issues that might otherwise be excluded in a mission area analysis. These R&D issues directly relate to the higher level needs of "maintain technological advantage" and "prevent technological surprise". While Volume I discusses these needs, which are directed responsibilities of the R&D effort (as specified in Air Force doctrine), they are not explicitly incorporated in the mission needs hierar-

chy. It would be difficult to do so, as we show in the next chapter.

IV. R&D Decision Environment

Introduction

In Chapter Three we pointed out that some of the problems with the MSSTP were due to the dynamic nature of the process and the environment in which it exists. Volume I of the MSSTP addressed the doctrinal and policy sources for military tasks in an attempt to describe the environment in which the space R&D advocacy process operates. It pointed out that to be responsive to future military requirements in space and to hedge against technological surprise, we had to do more than simply project current tasks into a future timeframe. The technique Volume I described to deal with these needs was to project threats and required capabilities through the year 2010. Based on these projections, tasks were defined to meet future mission needs in space. These were linked down through technology issues in a hierarchical structure to show connectivity between technology issues and future mission needs.

In this chapter we present a more expanded description of the environment in which the space R&D advocacy process operates. Several environmental factors are discussed which ultimately tie the R&D process to satisfying national interests. By no means is this discussion complete. The intent is to provide a flavor of the many external and internal factors that influence space technology advocacy.

This discussion primarily focuses on the linkage

between doctrine, one of the environmental factors we introduce, and space-related R&D. We show how an R&D strategy must be firmly founded in doctrine in order to satisfy national security objectives and support national interests. Our efforts here focus on providing a clear picture of what doctrine is and why it is essential that it be a major influence on any space R&D strategy. This discussion also establishes the unique relationship that exists between technology and doctrine. The purpose for describing our perception of the R&D decision environment is to provide a foundation for an alternative hierarchical model for evaluating space technology issues. The discussion in this chapter leads into the presentation in the next chapter of our hierarchy and qualitative criteria to evaluate technology issues (technology issue worth assessment).

The Environment

> What we have lost in military matters in this generation is time. Time has been our solvent, teacher, and our friend in all the wars of our history. It's no longer there and, in its place, we must substitute a readiness composed of several ingredients...modern weapons...autonomous mobility...professionalism [6:3-1].
>
> General David C. Jones

The military R&D environment is dynamic, uncertain, and complex. Environmental factors change in importance and scope, and these changes can impact R&D efforts in many ways. Despite the best of efforts, the identity, much less the impact, of these factors are often unknown. The dynamic

and uncertain nature of the environment, which is heightened by the number of environmental factors, the degree of interaction and dependency among these factors, and their combined effects on the military R&D process, contribute to this complexity.

In spite of this complexity, it is necessary to describe some of the important factors that impact the nature, aims, and objectives of military R&D. While such a discussion can never be complete, it does serve to focus attention on some of the critical factors to which R&D is particularly sensitive.

Description of the environment, and its affect on the nature of R&D, centers on six factors: operational requirements, projected threat, national security objectives and policies, resource availability, the physical environment, and doctrine. Although these factors are worthy descriptors, they are not necessarily independent nor collectively exhaustive. However, they adequately describe some of the important environmental interactions in the military R&D process. These interactions are illustrated in Figure 4-1. This chapter describes the military R&D environment in the context of these six factors. Preceeding our discussion of these interactions is a brief description of the nature of R&D, with emphasis on the sources, goals and responsibilities for research and development within the Air Force.

Nature and Aims of R&D. The United States prides itself on being technologically superior to all other

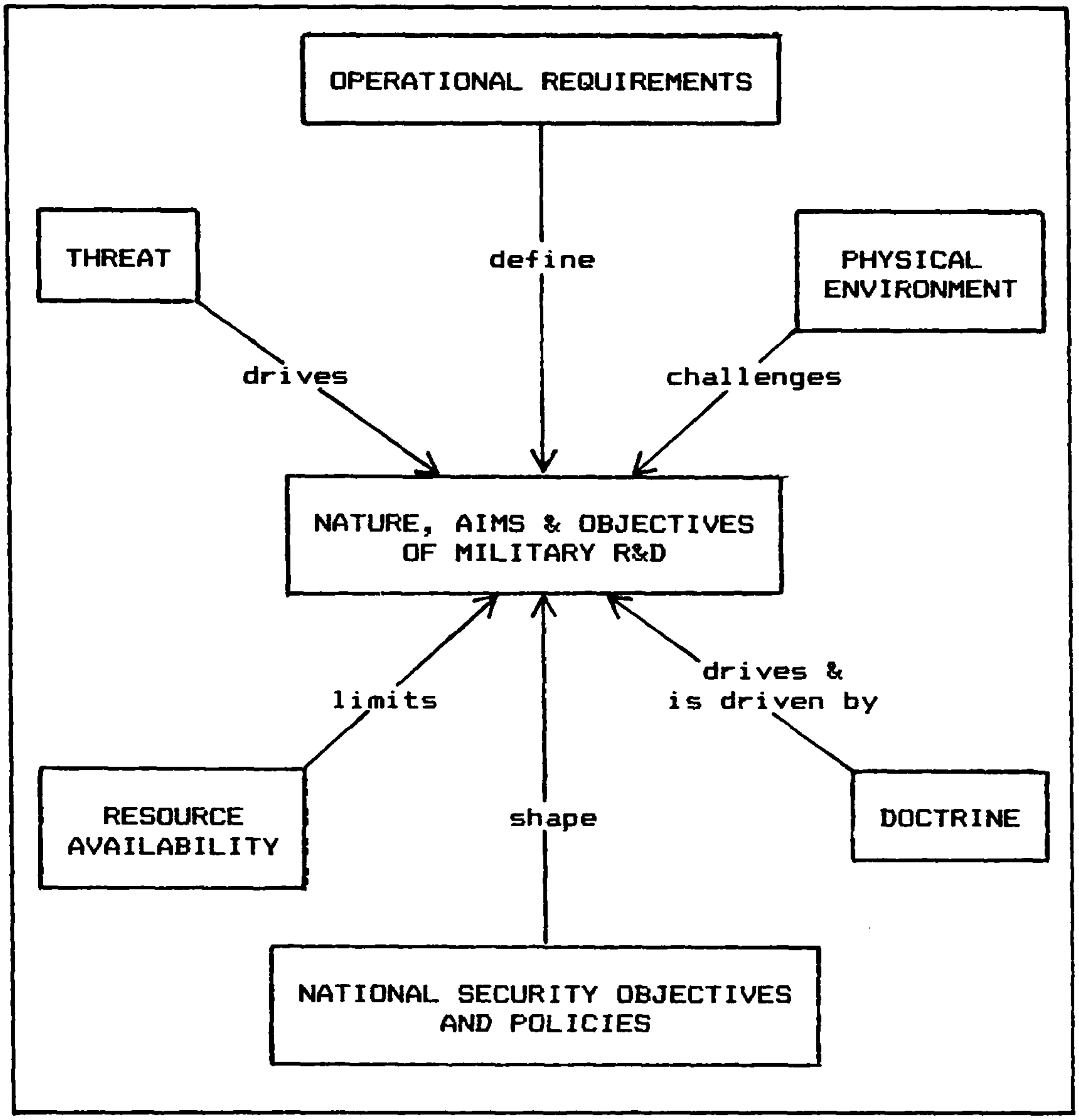


Figure 4-1. Military R&D Environment

nations. We have led the world in most technology areas over the last four decades. Our R&D superstructure (people, facilities, and organizations) and products have been the essential elements supporting this superior lead in technology. However, today our supremacy is being threatened on many fronts [112:71; 121:64; 255:46].

The Japanese challenge us in such areas as steel production, microelectronics, satellites, biotechnology, and artificial intelligence [255:46]. In fact, they have taken the lead in microelectronics and telecommunications technology, and are the top exporters in these high technology markets [247:61]. The Soviet Union and many European nations compete directly with us in exporting high technology weapons systems to nations throughout the world. The USSR has made significant technology advances in directed energy weapons [257:101] and threatens to make a technology breakthrough in space-based radar systems capable of detecting our SSBN fleet [259; 260]. We further discuss Soviet R&D efforts when we discuss the threat as an environmental factor.

The US response to the technology crisis under the Reagan administration has been to "create a climate conducive to research and development that would improve competitiveness and productivity" and to "forgo the 'government as subsidizer' role" [75:38]. Through various actions this administration has encouraged private industry to take the lead in developing and funding their own R&D efforts. For example, Reagan supports a bill to make permanent the 25% tax credit for incremental R&D expenditures (above a firm's average outlays over a previous three year period), which is currently due to expire on 31 December 1985. He also supports the Joint Research and Development Act (in joint committee as of October 1984) which provides

partial relief from antitrust laws to companies banding together to do research they might not do alone [104:42-43]. Several companies have already combined their resources into R&D "consortia" to push basic research in generic areas which benefit all participants [255:50]. There are many other examples where industrial interests and professional organizations have combined efforts to focus and apply R&D resources [4; 112; 121].

This does not mean that the federal government does not subsidize R&D. The proposed fiscal year 1985 budget includes $53.1 billion for R&D, a 14% increase over 1984. According to George Keyworth, the President's science advisor, the federal government has increased the level of funding "out of a sense of urgency attached to the loss of America's technological edge" [75:39]. However, the Administration has been selective in where the monies are applied. For example, President Reagan signed into law the Small Business Innovation Research Act in 1982. This act is designed to increase the amount of federal R&D funding to businesses with less than 500 employees. One of the major reasons for this legislation was that studies showed that small firms averaged 2.5 more innovations per employee than larger firms and commercialized these innovations one year faster and at 25% of the cost [48:51]. However, most of the increases in federal R&D funding have gone into military R&D efforts. In fact, over the last four years, federally supported defense related R&D has increased by 65%, while

non-defense R&D has actually decreased by about 30% [75:39].

There are several organizations and individuals who play a part in how these monies are spent. Congress, the Executive Branch, the Department of Defense, and each of the Services have dedicated organizations to oversee or manage DoD related R&D direction and spending. Within the Department of Defense, each Service has laboratories responsible for directly managing R&D programs, and the Defense Advanced Research Projects Agency (DARPA) manages R&D efforts that may jointly apply to more than one Service. A great majority of DoD related research and development is accomplished by private industry, either through government contracts, independent R&D (IR&D), or technology spin-offs resulting from commercial R&D efforts.

The Air Force Systems Command (AFSC) has overall responsibility for R&D management within the Air Force. Among other responsibilities, AFSC is tasked with planning, formulating, and executing research and exploratory developments consistent with Air Force policy and resource allocation and for managing an overall R&D program that is responsive to Air Force requirements [10:3]. The operational commands are responsible for identifying operational needs that cannot be met by existing systems and submitting these requirements for consideration or validation. AFSC is responsible for ensuring that operational requirements are addressed by R&D efforts designed to resolve operational shortfalls [9].

AFSC has five major product divisions which supervise various Air Force laboratories. These product divisions are: the Armament Division at Eglin AFB, Florida; the Electronic Systems Division at Hanscom AFB, Massachusetts; the Aerospace Medical Division at Brooks Medical Center, Texas; the Aeronautical Systems Division at Wright Patterson AFB, Ohio; and the Space Division at Los Angeles AFS, California. The Space Technology Center at Albuquerque, New Mexico, was formed in 1982 under Space Division to supervise the Geophysics, Rocket Propulsion, and Weapons laboratories [45:56]. Laboratories are charged with providing the Air Force "scientific, engineering, and analytical support in creating new weapons, vehicles, and equipment, and developing future concepts and capabilities." They also "provide the principal Air Force interface with the scientific and technological communities" and "support evaluation, analysis, and test activities of system program offices" [11:1].

A majority of the research and development work is not actually performed by the laboratories, but is contracted to various private industries and nonprofit research activities [143:53]. Key among the nonprofit corporations that support the Air Force are four Federal Contract Research Centers (FCRCs). These are the RAND Corporation, MITRE Corporation, Lincoln Laboratory of MIT, and the Aerospace Corporation. These nonprofit corporations were formed to help the Services "achieve operational and technological superiority" [86:70]. For example, the Aerospace Corporation provides

the Air Force with systems engineering and integration support for a variety of space systems.

R&D programs are identified, managed, and funded according to a structured format that lists various elements to identify each program (see Table IV-1 [10:5]). Air Force R&D program designators begin with the numeral "6" and are broken out into various categories. We discuss four categories of interest [8].

61xx programs are defined as basic research efforts. They are studies and experimentation designed to increase scientific knowledge directly related to long-term national security needs. Basic research not only provides the fundamental knowledge for solving identified problems, but also provides a foundation for subsequent research in defense-related technologies that may lead to new or improved military capabilities.

62xx programs deal with exploratory development. These programs range from fundamental applied research to sophisticated experiments to solve a specific military problem. They include studies, investigations, planning, programming, and minor development efforts. Exploratory development is designed to develop and evaluate the feasibility and practicability of proposed solutions and determine their parameters. Program control is usually exercised by level of effort funding.

63xx is the designator for advanced development programs. These are projects that have moved into the develop-

Table IV-1. Program Element Number Structure

PROGRAM	CATEGORY	ACTIVITY	SERIAL NUMBER	COMPONENT
6	4	3	Ø2	F

A Army
N Navy
M Marines
F Air Force

In combination with the second and third, identifies specific program element
Ø2-ABRES

BUDGET ACTIVITY
1==Technology Base
2==Advanced Tech Development
3==Strategic Programs
4==Tactical Programs
5==Intelligence/Communications
6==Defensewide Mission Support

CATEGORY
1. Research
2. Exploratory Development
3. Advanced Development
4. Engineering Development
5. Management and Support

PROGRAM
1. Strategic Forces
2. General Purpose Forces
3. Intelligence and Communications
4. Airlift/Sealift
5. Guard and Reserve Forces
6. RESEARCH AND DEVELOPMENT
7. Central Supply and Maintenance
8. Training, Medical/General Personnel Activities
9. Administration and Associated Activities
Ø. Support of other Nations

ment of hardware for experimental or operational testing (not items designed and engineered for eventual military use). They consist of investigative and analytical development planning efforts contributing to technology guidance. Program control is usually exercised on a project basis.

Lastly, 64xx programs deal with engineering development. These are development programs that are engineered for military use but not yet approved for acquisition or operation. They also include operational support projects consisting of numerous small individual items, not integral to a major project, that are being engineered for military use. Program control is exercised by review of individual projects.

All Air Force R&D efforts are categorized by one or more of these designators. For example, a given project could require both basic research (61xx) and exploratory development (62xx). However, operational system developments are not part of this formalized R&D program. Operational system development projects include R&D efforts directed toward the "development, engineering and test of systems, support programs, vehicles, and weapons that have been approved for production and Service employment." They are controlled by reviewing the R&D effort associated with each weapon system program element [10:2].

Fundamental to the Air Force R&D program is that research must be "oriented toward advancing the technology base and solving military problems." AFR 80-4, "Air Force

Policy On The Support of Research" also states that the research effort must "stimulate and support Air Force technical areas to prevent technological surprise and to guarantee technological leadtime, (as well as) provide a strong scientific base of fundamental knowledge and new ideas." Sufficient resources must be allocated to support a comprehensive research program that maintains "a balance between research done to solve specific problems and research done to stimulate and support the basic sciences that underlie future technology requirements of the Air Force" [12:1].

However, funding of basic research is severely constrained. The balance between basic research to support future, unspecified needs and R&D to solve specific known operational problems is often skewed in favor of the more immediate needs. There is concern that "technologies with high promise for near-term application could be overemphasized at the expense of others less urgent for now but indispensable for far-term systems" [45:57]. Nevertheless, given the limited resources available for R&D, the strategy of the Air Force R&D program today is to "go after those technologies that offer the highest payoff with low or limited risk in order to field capabilities that the Air Force needs at a cost the nation can afford" [67:39].

This concludes our discussion of the nature of R&D. We have only provided a "broad-brush" treatment of the subject. Our intent was to introduce the major players, factors, goals, and scope of R&D, with particular emphasis on the Air

Force R&D program. We have not addressed the causes for the technology crisis we face today, nor have we explored the problems dealing with defense-related industries and their inability or unwillingness to assume more of the burden for R&D. However, we have described some of the complexities inherent in the military R&D environment. Other authors cover these subjects in detail [63; 91; 92]. Succeeding sections further explore some of these complicating environmental factors.

<u>Operational Requirements</u>.

> Research, development, and acquisition programs assure our future warfighting capability. Operational concepts and requirements define the nature, aims, and objectives of the research and development effort [6:4-12].
>
> Air Force Manual 1-1

$$\boxed{\text{OPERATIONAL REQUIREMENTS}} \xrightarrow{\text{"define"}} \boxed{\text{R\&D}}$$

Fundamental Air Force guidance clearly describes the interaction between military capabilities and the R&D effort needed to provide these capabilities. Air Force Manual 1-1, "Functions and Basic Doctrine of the United States Air Force," states that operational requirements needed to perform assigned military tasks must be supported by a strong R&D program. It lists three responsibilities of this program. First, maintain superiority in basic research and enrich the technological base. Second, identify new systems and system improvements that meet near and long term needs

of aerospace forces. Finally, exploit new technology that can lead to new concepts of warfare systems [6:4-11,12].

Air Force Manual 1-6 "Military Space Doctrine" [8], further defines the specific relationship between R&D and the military role in space. It states that, within the Department of Defense, "the Air Force is the leader in space operations and in requisite technology development for force employment in the aerospace" [8:7]. Responsibilities in space are a direct extension of Air Force aerospace functions, missions, and tasks. The space R&D effort must support the development and deployment of concepts that perform or enhance Air Force missions and tasks.

In fact, AFM 1-6 discusses several space related R&D responsibilities. The first is to sustain the potential for military operations by applying superior space-related technologies. The second responsibility is to encourage innovation to take advantage of advances in science and technology. The third is to maintain a strong research and development base which is responsive to operational needs and ensures that space systems are able to meet military requirements. The next responsibility is to develop and maintain the capability to provide the research, development, testing, engineering, and life cycle support required to bring into being, and sustain, military space systems. The final responsiblity is to develop the technology base and research, development, and acquisition policies that accommodate procurement requirements for space systems

[8:7-8].

While basic Air Force guidance states that operational requirements must define the scope and nature of R&D efforts, in actual practice military capabilities are often limited or enhanced by the quality of the technology base. General Robert T. Marsh, former Commander, Air Force Systems Command, stated in a recent interview that the military instrument of national power is dependent on superior technology to provide "qualitatively superior weapons systems to deter aggression ... and to offset the numerical advantages enjoyed by our adversaries" [161:42]. This dependency is a result of several factors, the first of which is the increased capabilities advanced technology can provide. Also, the tight fiscal restraints on military spending have forced policy makers to look for alternatives to large, manpower intensive and costly force structures. Finally, a reluctance on the part of national leadership to maintain large standing armies during peacetime has led to reliance on highly sophisticated and superior weapon systems designed to counter enemy numerical advantages. This reliance on advanced technology has been especially prevalent in the Air Force.

General Marsh goes on to say that the role of research and development over the last thirty years has been to provide a "storehouse full of technology just waiting to be applied" [161:42]. In many cases R&D was pursued independently of specific military requirements, and, once a given

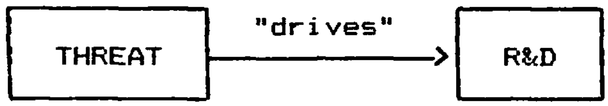
technology proved successful, it was used to meet military requirements. However, erosion in military R&D emphasis and significant commitment to R&D on the part of our potential adversaries means that we can no longer be complacent in believing the "storehouse" shelves will always be full.

And yet requirements for advanced technology are greater today than they have ever been and will only increase as military capabilities expand into space. General Marsh stated "there is no question but that our military future is heavily tied to space. The payoff from space-based assets is great today and promises to be even greater in the next century" [161:48]. Technology programs to support these capabilities will be expensive and, in many cases, will take years to develop with no guarantee of success.

This discussion has described the strong linkages that exist between R&D and Air Force operational requirements. Air Force guidance as expressed in AFMs 1-1 and 1-6 states that our R&D effort must support operational requirements. On the other hand, there are cases where technological advances serve to define new military capabilities, which, in turn, generate new requirements to take advantage of these new capabilities. Given this operational environment, the space R&D advocate must tie proposed space technology programs to operational needs. At the same time, he must justify exploring those technologies for which no direct connectivity with existing Air Force requirements can be

demonstrated. These technologies hold the promise for significant technological advantages and as a hedge against technological surprise from potential adversaries.

<u>The Threat</u>.



The threat drives military requirements which, in turn, drive military R&D. Projecting enemy capabilities and comparing these projections with current or forecasted capabilities to counter these threats should identify possible performance deficiencies. These performance deficiencies lead to identification of possible technology issues. These technology issues must then be addressed by R&D programs and resolved in a timely manner to ensure our weapon systems can counter the projected threat. In this respect, the threat is inextricably linked with operational requirements in defining and driving military R&D efforts.

Air Force doctrinal publications recognize this linkage. Missions and tasks are defined to destroy, neutralize, or negate enemy actions so as to resolve conflict on terms favorable to the interests of the United States. Projected enemy capabilities drive performance parameters for mission tasks to meet operational requirements which must be supported by the available technologies. Shortfalls in technology must then be addressed by the military R&D community.

While simply stated, the actual process of quantifying future performance parameters, which are then successfully addressed in a timely manner through R&D efforts, is complex and uncertain. First of all, threat projections are based on incomplete or uncertain information. Inaccuracies are magnified by the length of time the projection attempts to cover. Second, determining which mission tasks are affected by a particular projected threat can be a difficult process and the resulting performance parameters may not completely relate to projected enemy capabilities. Finally, there is no guarantee that an R&D program will provide in a timely manner the capability to counter the threat. It can take over 20 years to develop a technology to the point where it can be used in a weapon system. Indications are that some of the technologies being explored today may not be available until well into the 21st century [161:48]. The uncertainty faced by long-range planners and technologists is best expressed in the following quote by General Bernard A. Schreiver, who in 1959 asked:

> What appears to be a logical future program? The answer is not easy. It is very difficult to make a firm prognosis on military need during a twenty-year period for something as new and revolutionary as ballistic missiles, earth satellites, and space vehicles. We are somewhat in the same position today as were military planners at the close of the first world war when they were trying to anticipate the employment of aircraft in future wars [8:2].

Despite this uncertainty, some facts are known about the intensity of the threat and the challenges facing the

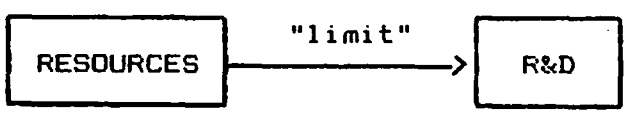
military R&D community to counter this threat. In fact, Secretary of Defense Caspar W. Weinberger stated in the preface to Soviet Military Power that the "USSR has greatly increased its offensive military capability and ... significantly enhanced its ability to conduct military operations worldwide" [257:96]. In the space arena, the Soviets are developing new, heavy-lift vehicles, designed to carry five times the payload of the U.S. space shuttle to low earth orbit. Within two or three years they will probably deploy a manned space station capable of accommodating up to twelve cosmonauts. And, by the 1990s, they are likely to deploy a large modular station that could house as many as 100 people. Such a station could be used for command and control, reconnaissance, and targeting functions, and, in the view of intelligence experts, "during wartime could perform more offensively oriented missions as well" [257:96]. The Soviets have already developed and tested an anti-satellite weapon, and may have a limited capability to blind some U.S. satellite assets with ground-based lasers. They have fully integrated their space capability into their military force structure and operate their space forces in conjunction with other military forces during major exercises.

Also, the Soviets have not ignored the importance of R&D in supporting their force structure. In a recent ten-year period the Soviet Union outspent the United States in R&D by more than $120 billion [161:42]. In 1960 the per-

centage of total military expenditures dedicated to R&D was about the same for both the United States and the USSR. By 1974 the Soviets' percentage of military funding committed to R&D had increased to three times that of the United States [161:49]. Likewise, they have made theft of western technology a major objective as well -- the extent of their commitment exemplified by the expulsion of over 100 "diplomats" from western countries during the last two years for their attempts to transfer sensitive technologies to the Soviet Union. In the words of Edward Teller, noted physicist and "father" of the hydrogen bomb, "we are not engaged in an arms race but rather a race of technology" [161:44].

Obviously, our military R&D effort must not only address threat projections. We must also anticipate that the Soviets' own R&D efforts could, and quite likely will, result in some technological advantages for them. Given their level of spending and effort devoted to military space applications, it is quite possible that Soviet advances in technology could negate our freedom of action in and throughout the aerospace. Our R&D effort must guard against this potential for technological surprise and its disasterous consequences.

<u>Resource Availability</u>.

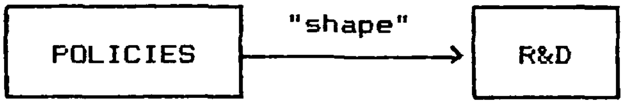


Research and development requires resources which are scarce and, hence, cannot possibly investigate all technology issues. Likewise, we have not maintained a level of spending in R&D to preserve the technological superiority needed to counter Soviet numerical advantages and technological advances. For example, there was no real growth in R&D funding since 1965. In fact, in terms of constant dollars, our technology investment today is only 75% of what it was in 1965. When viewed as the percentage of Total Obligating Authority (TOA), R&D funding accounted for just under 2.5% of TOA in 1965. In fiscal year 1984 it was only 0.8% of TOA [161:42,49].

While many recognize that increased R&D funding is required, it is likely that funding levels will continue below the levels necessary to guarantee a healthy R&D program. In fact, R&D must compete for a piece of the resource pie with sustainability, larger force structures, increased personnel costs, and operations and maintenance expenses. Additionally, space R&D must compete for limited funds with other Air Force R&D programs. Many of these programs have well established advocates and Congressional champions, making space R&D advocacy all the more difficult. Advocacy programs must not only demonstrate the relative worth of space R&D programs, but must also advocate for and generate additional funding to support a broad space technology base to guarantee a technological edge over the Soviets. In the words of General Marsh:

> The Air Force must face up to the problem that it's going to take increasing resources--over and above what we are devoting to it now--to maintain an adequate technology base. In terms of basic and applied research funding, we are at a nadir in absolute buying power [258:53].

National Security Objectives and Policies.



National Security Objectives and Policies shape the nature of military R&D. The basic security objective of the United States is to preserve our country as a free nation with its fundamental institutions and values intact. National policies support this objective and in turn depend upon the instruments of national power to implement these policies. The armed forces represent just one of many instruments that support national security objectives.

We will discuss these terms in greater depth when we present our proposed hierarchy in Chapter Five. However, it is important to note here just how these elements impact R&D efforts. In particular, National Policies ultimately constrain military R&D direction and scope, especially in the military space R&D community.

The focus of research and development is influenced by our evolving national security policies and our changing commitments through mutual security pacts and arms control treaties [6:4-12]. This influence is especially strong on space R&D programs. One of our national policies is to

honor treaty commitments and international law. This policy prohibits or restrains our freedom of action in space as it relates to deploying offensive or certain categories of defensive weapons in space. For example, treaties or international law prohibit: nuclear weapon tests in space; placing weapons of mass destruction in space; constructing military installations or fortifications on the moon or other celestial bodies; and developing, testing or deploying anti-ballistic missile systems based in space [8:3-4].

Other national policies have remained fairly constant through the years. These include such broad policies as: maintain sufficient military power to deter threats and defeat military actions against the United States; accept an equitable share of the collective defense effort with our allies; have available military action short of full-scale war, to signal our concern and intent; and ensure that our military actions complement our political and other instruments of national power [6:1-2].

However, with changes in administrations come changes in interpretations of what constitutes "sufficient," "equitable," and "intent." These can have disasterous impact on R&D direction and efforts. For example, when Jimmy Carter was elected President, he curtailed the B-1 bomber program, MX missile program, and put the U.S. ASAT R&D program on minimum funding in the hopes he could negotiate a meaningful agreement with the Soviets concerning use of weapons in space. While these programs have been

reinstated by the Reagan administration, costs are much higher and deployment dates slipped by several years.

Strictly speaking, national policies should only constrain operational requirements and concepts. In other words, except in specific cases, we can pursue R&D that potentially supports systems which if deployed, would violate treaties or international law. For example, an emotionally charged current issue is the space-based defense against ballistic missiles concept. The concept calls for placing weapon platforms in low earth orbits which would be capable of destroying enemy ICBMs before they strike targets in the United States. Although the concept calls for deployment sometime in the second decade of the 21st century, the R&D effort to provide required capabilities must begin today. Despite the enthusiastic support of President Reagan, this concept has not gained widespread support. Many critics cite the destabilizing effects of pursuing a capability not shared by our adversaries (and thereby increasing the possibility of nuclear war before we can deploy such a system) and the fact that deployment of a space-based ballistic missile defense system would violate the ABM Treaty. Since it is our policy to honor treaty commitments, these critics say that even pursuing R&D in these areas represents a "bad-faith" action on our part. This program is still facing an uncertain future in the military R&D environment.

The point is that when developing or advocating an R&D

program, we must recognize that national policy can be transitive and very sensitive to dynamic factors. To meet long-term R&D needs we must consider the constraining nature of current policies and incorporate within an advocacy program rationale for supporting R&D that may not be in step with the policies of today. For example, Air Force guidance, expressed in AFMs 1-1 and 1-6, requires us to maintain technological superiority and prevent technological surprise. Given the time it takes to successfully develop technology to the point where it can be used in weapon systems and the stiff competition for limited funding, R&D programs must stand on their own merits as they contribute to mission requirements and as a hedge against technological surprise.

<u>The Physical Environment</u>.

$$\boxed{\text{PHYSICAL ENVIRONMENT}} \xrightarrow{\text{"challenges"}} \boxed{\text{R\&D}}$$

The physical environment challenges the R&D effort. R&D programs attempt to exploit the advantages of operating in a particular physical medium and circumvent or counter the disadvantages and unique constraints presented by operating in that medium. For example, naval R&D efforts may be directed towards developing faster, quieter, and deeper running submarines for the U.S. Navy. They seek to take advantage of temperature differentials and current variations which confuse enemy sonar detectors. Along with this,

they must develop stronger materials to withstand the extreme pressures at the depths at which the submarines must operate. The space environment, similarly, has its advantages and disadvantages that challenge space R&D efforts.

General Thomas D. White is attributed with having brought the term "aerospace" into the Air Force vocabulary in 1958 as a means of linking the endo- and exoatmospheric media which, together, constitute the operating environment of the U.S. Air Force. His definition is still valid twenty-six years later:

> Since there is no dividing line, no natural barrier separating these two areas (air and space), there can be no operational boundary between them. Thus air and space comprise a single continuous operation field in which the Air Force must continue to function. The area is aerospace [6:2-1].

The aerospace medium has unique characteristics that offer significant advantages for military forces operating in the aerospace. Characteristics include unlimited horizontal and vertical three-dimensional movement and maneuver, and the capability to exploit speed, flexibility, and range to produce a wide range of effects and influences. Examples of beneficial effects and influences are: rapid projection of power; reduced time to respond (speed); perform a variety of actions (flexibility); and operate in any direction over great distances (range) [7:2-2].

In the outer reaches of the aerospace, these beneficial effects and influences are magnified. Space-based systems provide global coverage, do a variety of tasks, operate with

great flexibility, efficiency, and in some cases can perform these functions more economically than other systems [8:5,6]. In fact, the U.S. is dependent upon many space-based systems as the sole providers or performers for critical military tasks. General Marsh highlighted this point when he advocated the need for R&D efforts to provide survivability or defensive capabilities for our space assets, stating, "U.S. space capabilities have mushroomed and assumed a paramount role in this country's defense posture without commensurate action to ensure the survivability of these assets" [258:56].

On the other hand, operating in the exoatmosphere has some inherent disadvantages which must be considered. To operate in the medium one must first overcome the effects of gravity, which drives the cost for putting platforms in space. Because of its relative inaccessibilty, space systems must be designed for long life and high reliability, which further drive costs upward. While operating in a near perfect vacuum offers some advantages, it presents some significant challenges to a manned presence in space. The environment is unfriendly and alien to what we are accustomed to on earth. Cosmic radiation, gravitational and magnetic fields, solar heating, solar flare events, among others, all present unique technological challenges. Because of the high costs for getting to, and operating within the space medium, technologists and systems planners must carefully weigh the benefits for performing specified

missions in space against terrestrial based systems. Only if military utility, effectiveness, and suitability clearly weigh in favor of space-based alternatives should these be actively pursued.

Nonetheless, characteristics of the physical environment offer the space R&D advocate useful "ammunition" when arguing the benefits of space technology. Indeed, the space medium offers significant increases in military capability. A significant R&D effort will be required to take full advantage of the space environment.

<u>Doctrine</u>.

> At the very heart of warfare lies doctrine. It represents the central beliefs for waging war in order to achieve victory. Doctrine is of the mind, a network of faith and knowledge reinforced by experience which lays the pattern for the utilization of men, equipment, and tactics. It is the building material for strategy. It is fundamental to sound judgment [7:ii].
>
> General Curtis E. Lemay

Doctrine, the final environmental factor, drives, and at the same time is driven by, R&D goals and objectives. JCS Publication 1, "Dictionary of Military and Associated Terms," defines doctrine as "fundamental principles by which the military forces or elements thereof guide their actions in support of national objectives. It is authoritative but requires judgment in application" [7:v]. Both AFM 1-1 [6; 7] and AFM 1-6 [8] attempt to describe doctrine. AFM 1-6, "Military Space Doctrine," describes the role of doctrine in "equipping forces" and notes the dependence on both R&D and

the acquisition of systems:

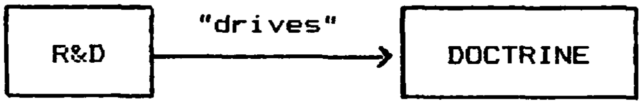
> The Air Force will maintain U.S. technological superiority in the aerospace and ensure a prolonged warfighting capability by developing the potential for combat operations in the space medium. The development of this potential requires an expanded awareness and an integral application of research and development, planning, and operational activities. A strong Air Force research and development base, responsive to operational needs, is essential to ensure that space systems are able to meet military requirements [8:10].

The thrust of this doctrinal statement is that R&D must be responsive to operational needs. This is the same point made earlier in our discussion of operational requirements as an environmental factor. Since doctrine represents the basic beliefs by which our military forces guide their actions in support of national objectives, then doctrine should also form the foundation for how these forces accomplish their assigned missions and tasks. Since tasks define or describe operational requirements, doctrine, indeed, appears to "drive" R&D efforts to support operational requirements.

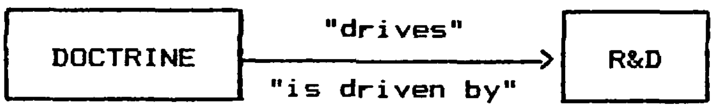
$$\boxed{\text{DOCTRINE}} \xrightarrow{\text{"drives"}} \boxed{\text{R\&D}}$$

However, in our discussion of operational requirements as an environmental factor which impacts the nature, aims, and objectives of R&D, we pointed out that there are times when advances in technology serve to generate military tasks or capabilities that were not defined prior to the technological advancement. Since tasks should relate to our doctrinal views, then, by extension, we must conclude that

"the development of emerging technologies may well influence the development of doctrine" [7:4-8]. AFM 1-1, "Functions and Doctrine of the United States Air Force," seems to support this position as well. "Doctrine is dynamic. It is constantly evolving as it adapts to changes in technology..." [6:6-6]. So, doctrine is often shaped by advances in technology brought about through R&D.



Thus, it appears that doctrine is unique from the other environmental factors we have discussed. It both influences, and is influenced by technology realized through R&D efforts.



Doctrine: What It Is And Is Not. We believe that a short discussion of doctrine, what it is and how it influences, and is influenced by technology, is useful in helping to explain this apparent dichotomy. Lieutenant Colonel Dennis M. Drew presents a new and refreshing perspective on doctrine and how it relates, or should relate, to strategy and planning within the Air Force. We use his article, "Of Trees and Leaves: A New View of Doctrine," [78] to introduce definitions and concepts that relate to this discussion on doctrine.

Drew argues that published Air Force doctrine is con-

tradictory and "conjures confusion and consternation" [78:5]. Much of the confusion is caused by the fact that published doctrine mixes several categories of doctrine indiscriminately without differentiating between the categories. Drew suggests that to understand doctrine, we must first understand that doctrine has three purposes: to preserve experience; to teach lessons learned from experience to others; and to be a general guide for actions. Three basic categories of doctrine proposed by Drew fulfill these purposes in varying degrees. These categories are fundamental, environmental, and organizational doctrine.

Fundamental doctrine is the foundation upon which all other doctrine is derived. It forms a "philosophy of war" and incorporates the basic beliefs about the nature and purpose of war and the relationship that exists between the military and other instruments of national power. Considered within fundamental doctrine are the "principles of war" -- the basic principles for employment of military forces. These are the same fundamental factors that successful military leaders through the ages have considered, to varying degrees, in their planning and execution of warfare. They include: objective, offensive, mass and economy of force, surprise, simplicity, maneuver, security, unity of command, defense, timing and tempo, and unity of effort. Fundamental doctrine considers and interprets these principles of war and their relationship to the pursuit of national goals.

Fundamental doctrine is fairly stable. It is based on

basic concepts rather than contemporary techniques of warfare. Because fundamental doctrine is insensitive to change, it is also "relatively insensitive to politics and technology. It does not rely on the political philosophy that controls the military instrument nor does it depend on the sophistication of the weapons that military forces can use" [78:8]. Fundamental doctrine forms the foundation for environmental doctrine.

Environmental doctrine is a "compilation of beliefs about the employment of military force within a particular operating medium, often including statements concerning the unique purposes and capabilities of forces operating in the medium" [78:8]. It is narrower in scope than fundamental doctrine, and is more parochial by emphasizing operations in a particular medium. Environmental doctrine can also be relatively insensitive to politics and other contemporary constraints, but it is influenced by geography (or the physical environment) and technology. In fact, aerospace (environmental) doctrine is "totally dependent upon technology and increasingly dependent on technology's many new gadgets" [78:8].

Organizational doctrine addresses basic beliefs about the operation of a particular military organization and incorporates constraints, current capabilities, and consideration for national cultural values and policies. It discusses the roles and missions assigned to organizations, current objectives, and force employment principles as

influenced by the current situation. As such, it is not "timeless" -- it is heavily influenced by politics and other environmental constraints.

There are no clear-cut boundaries between these doctrinal categories. Fundamental doctrine tends to be more abstract than either environmental or organizational doctrine. In fact, Drew describes it as the "relationship of military force to other instruments of power" [78:7]. Environmental doctrine (which for our purposes we describe as "aerospace doctrine" to reflect the connectivity with the physical medium in which Air Force forces operate) is slightly more dynamic than fundamental doctrine, and certainly more concrete. Emphasis is on potential applications and operations within the physical medium. Environmental doctrine is bounded by the physical environment and influenced by technology. In fact, it is technology that often drives the direction of environmental doctrine. Organizational doctrine, also defined as operational doctrine, is very dynamic. Emphasis is on the current way a military organization perceives its assigned missions and how it accomplishes those missions (through tasks). Although firmly founded on fundamental doctrine and heavily influenced by environmental doctrine, operational doctrine is still constrained by what is allowable or possible under existing policies, resources, and technologies. We will show that it is organizational doctrine, through operational requirements, that drives current R&D efforts.

We find when we analyze published doctrine that it mixes all three categories of doctrine. For example, AFM 1-1, "Functions and Basic Doctrine of the United States Air Force", discusses the principles of war (fundamental doctrine) and aerospace applications of the principles (environmental doctrine) in its Chapter Five. AFM 1-6, "Military Space Doctrine", likewise highlights environmental doctrine, as expressed in this statement: "the medium of space provides an unlimited potential and opportunity for military operations on which the Air Force must capitalize" [8:iii]. However, for the most part both publications are representative of organizational doctrine in that they relate existing restraints imposed by policy, treaty, and laws on the manner in which the military instrument (the Air Force) seeks to support national policies and interests.

<u>Doctrinal Influences on the R&D Process</u>. From this perspective we see that the strong emphasis in the MSSTP for linking technology issues (drivers for R&D) to operational requirements (military tasks) is in consonance with organizational doctrine. Since organizational doctrine represents the way we perceive how to use forces to meet current and projected threats, it should form the basis for the specific tasks necessary to carry out the strategies and tactics, since these are, or should be derived from doctrine [78:10]. Analysis of tasks reveals operational requirements. These ultimately define R&D requirements necessary to build the systems to meet required operational

capabilities. These relationships are shown in Figure 4-2.

```
   Policies
      |
Organizational
   Doctrine
      |
 Strategy ---> Tasks ---> Defines ---> Systems ---> R&D Rqmts
               Derived    Ops Rqmts          \         /
                                              Resources
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Figure 4-2. Linkage Between Operational Doctrine and R&D

We can now relate the hierarchical approach that the MSSTP process used to link mission tasks and technology issues to the concept of organizational doctrine. Recall that Volume I of the MSSTP derived tasks through mission area analysis by projecting threats for various timeframes and the required capabilities necessary to meet the threat. This analysis is almost identical to that outlined in AFR 57-1, "Statement of Operational Need (SON)", which provides regulatory guidance to Air Force organizations on how to formally identify operational needs [9]. Once operational needs are determined, they can be compared against projected capabilities. Shortfalls are identified as technology issues that R&D efforts must resolve. Thus, we have shown that R&D is responsive to (driven by) applications of organizational doctrine through operational needs.

At first glance it may appear that a methodology that can identify projected operational requirements and the technology issues that must be resolved to meet these

requirements would be sufficient for surfacing the vast majority of critical R&D efforts. However, there are problems with adopting this single approach. We have already pointed out in Chapters Two and Three the inherent inaccuracies with most projections based on subjective judgments. Recall that a majority of the inputs for the MSSTP are derived from such estimates. So there is no guarantee that all possible operational needs for the future will be identified. If all possible operational needs are not identified, then it stands to reason that not all potentially critical technology issues will surface. Consider the following discussion which shows that all critical issues may not, or are not, identified by a mission area analysis that matches operational needs to technology requirements.

To derive operational needs through a mission area analysis, it seems reasonable to expect consensus on what the important military tasks are that ultimately define operational needs. And yet with respect to military applications i, space, a debate continues concerning the proper role of military forces in this part of the operational aerospace medium. General Henry, Commander, Space Division, discussed the essence of this debate in an interview in June 1982. He said that "we have a debate as to what space operations are, and whether we're (Space Division) still in R&D or operations" [31:38]. In the same interview General Henry pointed out that the DoD was attempting to find out what the military mission in space really is. From his

perspective, "the only practicable military mission that we have come up with yet is still the collection, movement, and dissemination of military information" [31:36].

Hardly a year later, General Marsh, the Commander, Air Force Systems Command, stated that "there are all kinds of space capabilities one can conjure up beyond the limited spacecraft of today that simply go around the earth due to the laws of physics." He stated that a number of the most promising R&D options concern military operations in space. "In the Air Force's view," he said, "space is a place, not a mission, and it may be both feasible and necessary to conduct a broad range of operations from there in the future" [67:39].

There is clearly a wide difference of opinion between these two senior Air Force leaders concerning the military role and potential tasks in space. General Henry likened the debate to similar debates during the mid-1920s when aviation was still in its infancy and little consensus existed concerning military applications for the airplane [31:38]. However, even if everyone agreed to what the operational needs for space were, some experts doubt that an operational needs assessment would identify all the critical technology requirements for the future.

For example, during recent testimony given before the House Defense Appropriations Subcommittee, Allen E. Puckett, Chairman and CEO of Hughes Aircraft, said, "almost none of the dramatic new technologies of this century was conceived

as a result of the statement of a military requirement, or the specifications in a Defense Department contract" [115:61]. He cited examples of technology advances that had resulted from independent research and development (IR&D) on the part of private industry that included: radar, the airplane, jet engines, rocket engines, semiconductors, lasers, microcircuits, communications satellites, and nuclear weapons. "The conception and initial exploration of these ideas were carried out by members of our engineering and scientific community," he said, "working in an environment which allowed and stimulated novel and unorthodox thinking" [115:61].

We propose that these concerns can be satisfactorily addressed from an environmental doctrine perspective. Certainly the debate that is ongoing concerning applicable military missions and tasks in space has environmental doctrine overtones. General Marsh was clearly speculating on the potential for performing military tasks in space and utilizing the advantages of the medium for military purposes. In fact, we believe that much of the confusion and debate surrounding the military role in space can be explained as a "clash" between organizational doctrine and environmental doctrine.

Recall that environmental doctrine is more "free wheeling," heavily influenced by technology, but relatively unconstrained by policies and current, "accepted" ways of doing things. Another way of approaching environmental

doctrine is to consider it as an application of the principles of war, as addressed in fundamental doctrine, in a particular operational medium. In this regard environmental doctrine represents a "no-man's land" when it comes to doctrinal agreement with national policies.

We pointed out that fundamental doctrine does not rely on the political philosophy that controls the military instrument. At the other extreme, we showed that organizational doctrine is directly influenced by current politics and policy. If we accept that environmental doctrine is defined somewhere between the two, with no clear delineation where one stops and the other begins, then we should expect areas where environmental doctrine conflicts with organizational doctrine. Therefore, aerospace environmental doctrine adherents may disagree with accepted military "truths" (as represented by organizational doctrine) in their advocacy of potential applications of the principles of war in the aerospace environment. As new applications for military tasks in the environment are proposed, discussed, and either accepted or discarded, we can expect conflict to exist between organizational doctrine and proposed environmental doctrine.

New military capabilities, or applications within the operational environment, are usually first argued from the perspective of environmental doctrine. There are times when technological advances brought about (or promised) by R&D efforts can, themselves, define new military capabilities

that support national security objectives. The advent of new technologies often inspires environmental doctrinal thinkers to propose ways in which the technology can improve the conduct of military operations in the operational medium. The following examples serve to illustrate these points.

In the early 1920s General Billy Mitchell and Field Marshall Guilio Douhet proposed the concept of strategic bombing. Aircraft, flying higher and faster than pursuit aircraft and with the capability to defend themselves, could deliver large numbers of bombs deep into enemy territory. By hitting and destroying enemy targets deep within the enemy's own territory, strategic bombing could ultimately win wars, relegating land and sea forces to defensive or "holding" operations until the strategic bombing offensive got underway. Interestingly enough, these theories were advocated long before R&D delivered bombers capable of performing these missions (the B-17 and B-29). Nonetheless, this was a case where an idea (generated because the aircraft, a relatively new invention, represented increased potential and different capabilities for supporting national security objectives) evolved into doctrine and drove the development of new weapons systems to perform new, previously unthought of tasks.

Likewise, the development of nuclear weapons was a case where technological advances drove the development of doctrine. When the Soviets developed a nuclear capability

it forced military strategists and national leaders to reevaluate all previous concepts of warfare within the context of nuclear war. From this, the doctrine of deterrence was born -- a doctrine the U.S. adheres to today.

A more recent example points to where the concurrent application of environmental and organizational doctrine can conflict. It also serves to highlight the important differences between the two categories of doctrine, and the impact both can play on the R&D process. This example is the Strategic Defense Initiatives (SDI).

The SDI represent a group of concepts that individually, or in some cases collectively, define a space-based defense against enemy ballistic missiles. Ballistic missiles are most vulnerable in their boost and post boost phases of their ballistic trajectories in the exoatmosphere. Space weapons systems, such as lasers, particle beams, and/or hyper velocity kinetic energy platforms can theoretically destroy or neutralize the vast majority of an enemy's ballistic missile force before they ever reenter the atmosphere (See High Frontier [105] and Ballistic Missile Defense [47] for greater indepth discussion of this subject).

The idea of a defense against ballistic missiles is not new. In the early 1960s we demonstrated a capability to intercept an ICBM in space, and were well underway towards full scale development of the Sentinel and Safeguard anti-ballistic missile systems when we signed the ABM Treaty with the Soviets in May, 1972. However, between then and March,

1983, when President Ronald Reagan made comprehensive missile defense an explicit national goal, very little serious consideration was given to the idea [47:2].

Two reasons stand out for this hiatus; policy considerations and the inability of technology to provide (or promise to provide) the capability for a reliable ballistic missile defense. Former Secretary of Defense Robert MacNamara summarized the policy considerations that went into our country's decision to forego a defensive capability in 1972 during a recent television documentary on the SDI [253]. He said that back then we did not have the capability to deploy a reliable ABM system and that efforts to secure the required capability would be destabilizing to deterrence. At that time we had clear strategic offensive superiority over the Soviets, and deterrence was based on Soviet awareness of this capability and their perception of our will to use it in retaliation for any strike against the U.S. or its allies. He opposes development, or even research into strategic defensive systems today, for many of the same reasons.

During the Carter administration, very little direct effort was expended on SDI related concepts. However, towards the later part of Carter's term in office, advocates of space-based ballistic missile defense systems became more vocal (Again, Gen Graham's High Frontier [105] being one of the more famous essays). These champions of "star wars" [253] weapons pointed out that technology, and the promise

of future technological advances, made the idea feasible. President Reagan, as pointed out earlier, agreed that the concept had merit and directed an all-out effort to explore the options.

Secretary of Defense Caspar Weinberger, appearing on the same documentary as MacNamara, stated that the capability to protect against an ICBM attack would represent a stabilizing influence and allow us to draw down strategic offensive forces. Pursuing the R&D necessary to prove the feasibility to deploy defensive systems in space would not violate the ABM Treaty. However, Weinberger conceeded that should we decide to deploy the system, we would have to renegotiate or abrogate the treaty [253].

Weinberger provided additional rationale for the necessity of the SDI when he presented the Fiscal Year 1985 Five Year Defense Plan to Congress. He cited the Soviets' advanced ballistic missile defense technologies, the fact that they alone have an operational ballistic missile defense, and that unilateral breakthroughs and deployment of an advanced system would "weaken deterrence and threaten U.S. security" as reasons why the U.S. should pursue SDI related technologies. "U.S. research efforts," he said, "will provide a necessary and vital hedge against the possibility of such a one-sided Soviet deployment" [256:84].

Today the debate continues, despite the high level support from President Reagan. Critics of SDI cite the destabilizing effects of pursuing a reliable defense against

ballistic missiles. They believe that the Soviets would launch an attack before we could ever deploy the system if they thought the system could successfully negate their ballistic missile force. The point of this discussion, however, is not to address the pros and cons of SDI, but to highlight the doctrinal interactions and relationship to the R&D process.

We can see how elements of both organizational and environmental doctrine played, and continue to play, major roles in the debate. Until Reagan directed the country move forward towards exploring the feasibility for a space-based ABM system, the military gave it very little consideration. From an organizational doctrine perspective, the military instrument was guided by the policy of deterrence, as represented by MAD (Mutual Assured Destruction). Deterrence would be maintained by the military ensuring it had the strategic offensive capability, represented in the strategic triad (manned bombers, land-based ICBMs, and submarine launched ballistic missiles), to survive a first strike and retaliate with sufficient force to assure the destruction of the aggressor's homeland.

On the other hand, advocates of SDI argue from an environmental doctrine perspective, extolling the advantages that a "real" defense against ballistic missiles would provide. R&D efforts, especially in the areas of lasers and particle beams, also seemed to indicate that the possibility is real that such systems can be built and deployed in the

near future [253].

These discussions point out that considering potential military tasks, and the R&D necessary to support them, can be viewed from an environmental doctrine perspective. This perspective promotes "free thinking" about the possible military applications available within an operational medium like the aerospace, and is not constrained by current policies, or strategies and tactics (both derived from organizational doctrine), or accepted ways for doing things. We showed how application of environmental doctrinal thinking exploits technology, looking for new ways to employ technological breakthroughs in the operational medium. At the same time, technology feeds on environmental doctrine, which often serves to drive new requirements for R&D.

We propose that R&D should not be evaluated solely on its linkage to operational requirements as influenced by organizational doctrine. In fact, we argue that by incorporating environmental doctrine into mission area analysis we can better derive future operational requirements simply by broadening the scope of tasks considered. This is in fact what the MSSTP process does, since it includes concepts for systems we are currently restricted by national policy from building.

When we present our hierarchy we argue that an environmental doctrine perspective also allows us to directly consider two important R&D needs not directly supported in a mission needs hierarchy such as that used by the MSSTP.

These are "preserve our technological superiority" and "prevent technological surprise." Both of these needs are identified in published Air Force doctrine [6:4-11,12; 8:9] and often cited in the literature [5:34; 75:39; 112:71; 115:62; 121:64; 161:44].

Summarizing, doctrine is intimately linked to R&D. As a foundation for basic beliefs about the conduct of warfare, doctrine defines operational requirements, which, in turn, drive the R&D effort needed to meet specific performance parameters to accomplish these operational requirements. We defined this type as organizational or operational doctrine, and said it was dynamic, constrained by policies, and limited by accepted ways of doing things.

On the other hand, we pointed out that advances in technology can actually drive the development of doctrine, as was the case with the development of nuclear weapons. In other cases technological advances demonstrate the potential to do new missions in support of national security objectives, which evolve into doctrine, which, in turn, challenge the R&D community to develop new military capabilities to support the new doctrine. The development of strategic bombing is a specific example. These examples are applications of environmental doctrine, which we said was less influenced by current thinking and policies, and more "free-wheeling" than organizational doctrine. Proponents of environmental doctrine are heavily influenced by technology and its application in supporting potential military tasks

in the operational environment.

We also pointed out some drawbacks with identifying critical technology issues through mission area analyses (mission needs hierarchy). It is difficult to gain consensus on what the applicable tasks are for military missions in space. Simply stated, mission area analyses may not successfully identify all critical technology issues. As pointed out, some of the more important technologies we use today were not surfaced by an operational needs assessment. We showed how these concerns could be addressed within the context of environmental doctrine in considering future military R&D requirements.

Summary of the Environment.

> In light of the Soviet Union's continued pressure upon the qualitative edge and the long lead time required to develop these capabilities, we have no choice but to pursue them now. We must seek the revolutionary technologies of the future--the "big wins" on the technology battlefield that will provide future generations of Americans with the same qualitative edge that we have enjoyed [161:49].
>
> General Robert T. Marsh

We discussed six factors that influence the environment in which military space R&D advocacy must operate. Operational requirements drive the R&D process and, in this respect, space technology advocacy must give this interaction strong consideration. Space technology efforts should be linked to military task requirements. The projected threat drives performance parameters to which the R&D

program must be responsive. If the capability exists to depict and analyze R&D efforts on the basis of linkage to operational requirements, then the space R&D advocate should strongly consider using such a framework for advocating R&D programs. Indeed, the foundation for relating R&D to operational requirements has already been established in basic Air Force doctrine.

On the other hand, we showed that it is not always possible to directly link R&D efforts to operational requirements. We must consider that our potential adversaries could develop advanced technologies of their own that could significantly alter the balance of power and present a serious threat to our national interests. Our technology base and R&D effort must guard against the possibility of technological surprise. Likewise, considering doctrine and the physical environment of space, the potential for developing significant technological advantages is unlimited in the space medium. We showed how viewing doctrine from various perspectives can aid the space R&D advocate in identifying technology issues and in developing a space technology advocacy plan. We pointed out that the space R&D advocate must consider the hedge against technological surprise and the potential for technological advantage in his advocacy program in a way that is easily understood and accepted. An environmental doctrine approach makes this possible.

Finally, we discussed R&D in the context of national

security objectives and policies and resource availability. These environmental factors actually represent constraints on R&D. Resources will always be limited, and funding of the Air Force R&D program is going to be a critical issue for some time to come. The space R&D advocate must consider this factor in his advocacy program -- either by showing how space-based systems are more economical than terrestrial-based systems or by clearly demonstrating that the strategic and technical utility of the advocated technology makes the required expenditure worthwhile. While AFM 1-6 states that all Air Force missions can be accomplished or supported from space, national policy restricts the military instrument from deploying certain types of systems in space to support national security objectives [8:8]. Many critics of space systems refer to these policy constraints as reasons why R&D efforts should not be pursued that potentially provide significant military advantages to the United States. We have discussed the impact that time -- as expressed by the length of time it takes to bring a technology program to fruition in a weapons system -- has on supporting operational requirements with our R&D program. We cannot afford to be limited by policy considerations in advocating space R&D programs to meet known, projected, and unknown threats for the future. The threat will not allow recovery from mistakes made twenty years in the past.

In the next chapter we present our hierarchy and criteria for assessing technology issues. Using the

foundation we have built here, as well as information from our discussion of the MSSTP in Chapter Three, we show an alternative approach to the mission needs hierarchy implicit in the MSSTP. We also show the linkages between National Policies and military missions, which were implicit in the MSSTP, to display a more complete hierarchy. Most importantly, we show how the needs "maintain our technological advantage" and "prevent technological surprise" can be linked directly in the hierarchical structure to other than military missions. The criteria we introduce relate to all these areas.

V. Proposed Hierarchy for Space R&D Advocacy

Introduction

We concluded Chapter Three with a diagram of the MSSTP hierarchy (figure 5-1). We called this a "mission needs" tree because it linked technology issues through various levels to DoD missions. This hierarchy was intended to show the connectivity between technology issues and DoD mission tasks.

We pointed out in Chapter Three that this mission needs structure was derived through mission area analysis by evaluating military tasks from the perspective of utility, projected threat, and required capabilities. The intent of this analysis was to define operational requirements for projected tasks and to identify technology requirements necessary to meet these requirements.

We also noted in both Chapters Three and Four some of the problems with the MSSTP hierarchical structure and process. We said the hierarchy was not complete since it did not explicitly show all the linkages between military missions and national needs. Furthermore, we stated that the structure may not surface all critical space technology issues. Specifically, we pointed out that using concepts to help identify technology issues may not provide a comprehensive list. Other methods exist to determine space technology issues. These alternative methods should be considered. For example, we noted that if performance

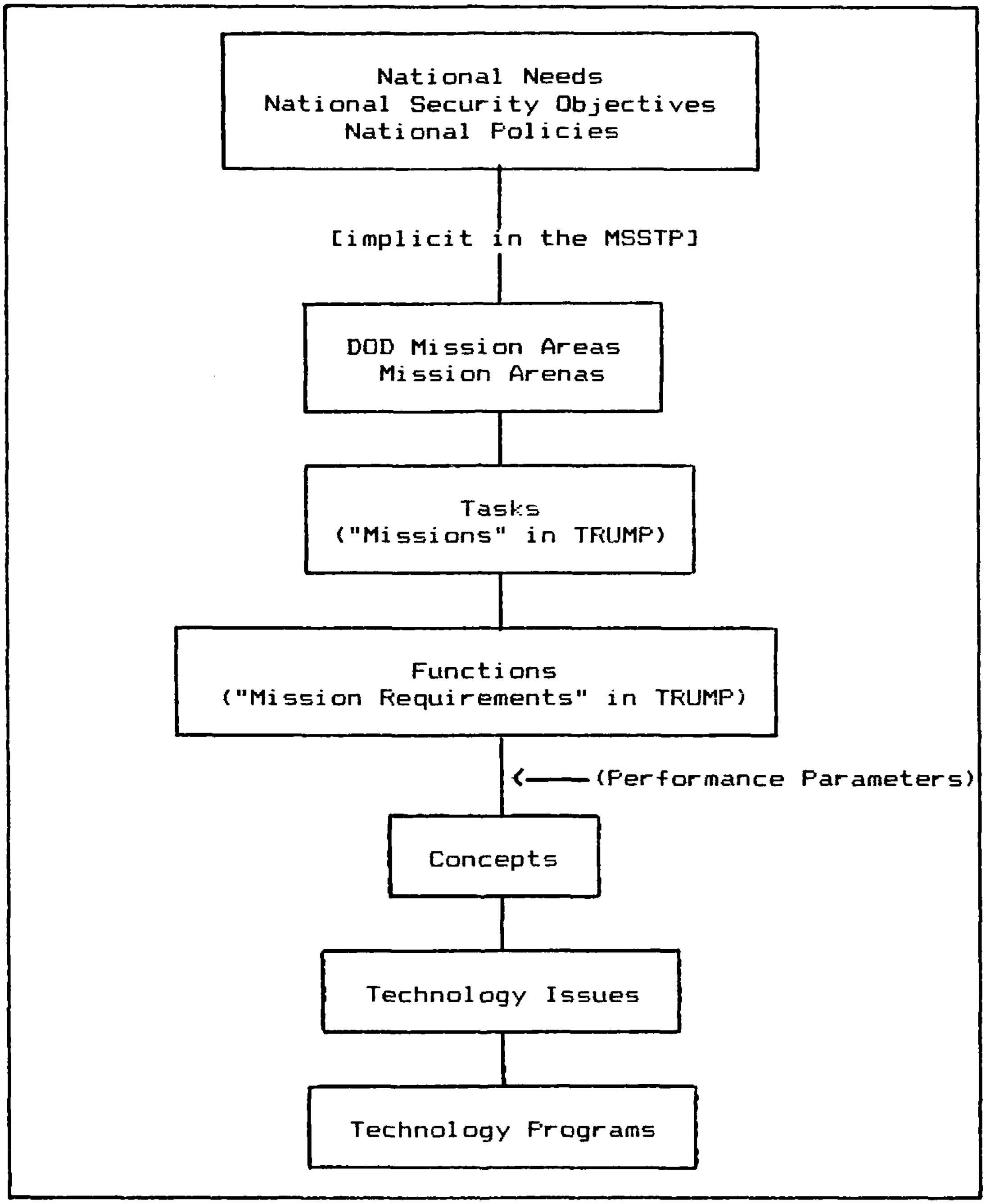

Figure 5-1. MSSTP & TRUMP Hierarchy

parameters were completely specified for all tasks, then the difference between required performance capabilities and projected technology to support these capabilities could

define technology issues. However, since performance parameters are not specified for all tasks in the MSSTP, some technology issues may go undefined. Finally, we suggested that mission area analysis does not identify all critical technology issues for the future and showed examples where important technologies in use today by the military were developed completely independent of an operational needs assessment.

In this chapter we propose a more comprehensive hierarchical structure to model the R&D process. We first discuss the benefits of organizing complex problems in hierarchies. This discussion introduces our proposed hierarchy. It incorporates a mission needs tree, but shows linkages from missions to national interests for completeness. We have explicitly included environmental doctrine in our descriptions of missions and tasks, so there are some differences between our mission needs tree and that presented in the MSSTP.

However, the mission needs branch is only one part of our hierarchy. We also show connectivity from technology issues to higher level needs through an alternative linkage -- the scientific-technological linkage. We believe this linkage provides an additional method for identifying and assessing technology issues, many of which would not surface through mission area analysis alone.

We next discuss three criteria we derived to assess technology issues. These criteria are intended to be quali-

tative measures which the space R&D advocate can apply to rank order a list of technology issues. They appear at the lower end of our hierarchy to show their linkage to technology issues.

Finally, we show the linkage of the proposed hierarchical structure to a space technology advocacy model which considers the environmental factors we discussed in Chapter Four. This serves as a lead-in to the discussion of the decision support implementation of our methodology covered in Chapter Six.

Hierarchical Ordering.

Most management science texts describe problem definition as one of the most difficult and yet most important steps in the problem solving process [44:8; 198:4; 206:63; 218:246]. Among the difficulties inherent in defining and scoping a complex problem are identifying all relevant elements influencing the problem and recognizing and/or understanding the relationships between elements. It is not a trivial matter to establish how the various elements "can be communicated, organized with respect to structure, and evaluated" [206:63]. The ultimate goal then in the problem definition stage is to identify all relevant criteria (elements) and organize or partition the problem into manageable parts so interactions among relevant elements clearly stand out [206:64].

A hierarchical ordering of elements is a logical method-

ology for organizing and displaying the various elements and their relationships relative to each other. A hierarchy provides an easy to understand framework for describing a problem or "process that fits observations of the real world" [218:246]. Ordering elements in a hierarchical structure is a natural, human tendency when attempting to grasp difficult concepts. We all try to "put things into perspective," "determine priorities," and logically organize factors by degrees of importance. Most of us are familiar with Maslow's hierarchy of needs and all of us have been exposed to organizational charts, chains of command, and other hierarchical representations of real world processes or structures.

Hierarchies are especially useful for defining needs, desires, and higher level goals and objectives which are subjectively described and cannot be directly quantified or measured. These higher level goals and objectives can then be related to lower level elements that can be specifically quantified and used as performance measures for the less quantifiable higher level elements [288:17]. Organizing elements in this type of subordination ordering helps the decision maker focus on critical interactions and also provides a means of clustering or breaking the problem into smaller, more manageable parts without losing connectivity between elements. In general a hierarchical structuring of relevant elements bearing on a problem provides a clearly understood framework. With this structure, the problem can

be analyzed and evaluated from a variety of perspectives and methods.

There are few "rules" for hierarchies. Elements in a hierarchy are loosely defined as "criteria," and include all "attributes, goals, and objectives which have been judged relevant in a given decision situation by a particular decision maker" [288:17]. Normally, elements at the same level represent "irreducibly simple part(s) of a system" [206:13].

At the top of the hierarchy are the "axiological objectives" that represent the needs, higher level goals, and value system of the decision maker and/or his environment [206:63]. At the bottom are objective measures, performance parameters, or descriptors that can be quantified (surrogate criteria) and thus used as measures to determine the degree of achievement for realizing higher level, more abstract goals. In between are various levels of goals, objectives, and attributes that further describe the process being modeled. They are linked, both from above and below on the hierarchy, by the transitive relations of "how" and/or "why" to show clear connectivity. These may be causal relationships where satisfaction of higher level elements depends first upon satisfying lower level objectives. They may also be relational linkages where satisfaction of a lower level element contributes to the actualization of higher level elements.

Ideally, elements at the same level should be mutually

exclusive (independent of one another) and collectively exhaustive (together they cover all contingencies). In most complex, real world problems this is not possible due to the interdependency of elements and an inability to clearly break out and clump all elements according to neatly bounded and narrowly defined standards. Schoderbek, et. al. [213] state that "absolute subordination among parts does not exist. In fact, the division between absolute 'parts' and 'wholes' is arbitrary, if not meaningless" [213:264-265].

Despite these difficulties, hierarchical structures offer many advantages. They help the decision maker scope the problem, graphically describe perceptions of real world processes, determine relative degrees of importance between various elements, and break complex problems down into more manageable parts. They provide "an organized but complex framework that allows for interaction and interdependence among factors" and enable us to "think about them (factors) in a simple way" [198:4]. Hierarchies, in and of themselves, are simple. They represent simplified representations of difficult conceptual and contextual relationships. It is the identifying and ordering of all relevant elements that can be most demanding. However, taking the time to clearly structure relevant elements is a necessary and worthwhile first step in defining and scoping complex problems. The resulting structure then provides a reasonable framework for subsequent analysis.

Hierarchical Structures and Space R&D Advocacy.

As discussed in Chapter Four, the R&D environment is not easily understood nor described. A hierarchical framework can provide a pictorial representation of the space R&D environment as it relates to Air Force missions, DoD missions, national policies, national security objectives, and national interests. We introduced this chapter with a summary of the hierarchical structure discussed in the MSSTP, and reiterated some of its shortfalls. In this section we present an alternative hierarchical structure that we believe represents a more comprehensive "picture" of the elements and their relative ordering with respect to each other. The hierarchy we develop is shown in Figure 5-2.

We make three major changes to the MSSTP hierarchy. The first is explicitly describing the linkages from national interests at the top down through missions, which was not done in the MSSTP. Aside from this, the left side of our hierarchy appears very similar to the "mission needs" hierarchy of the MSSTP. However, since we incorporate environmental doctrine in deriving responsibilities, missions, and tasks, descriptions of these elements will vary somewhat from those in the MSSTP (see Appendix G).

The second change is more significant. Here we show linkage between technology issues and the scientific-technological instrument of national policy. As developed in our discussion of the relationship between R&D and doctrine, doctrine both drives and is driven by R&D. In

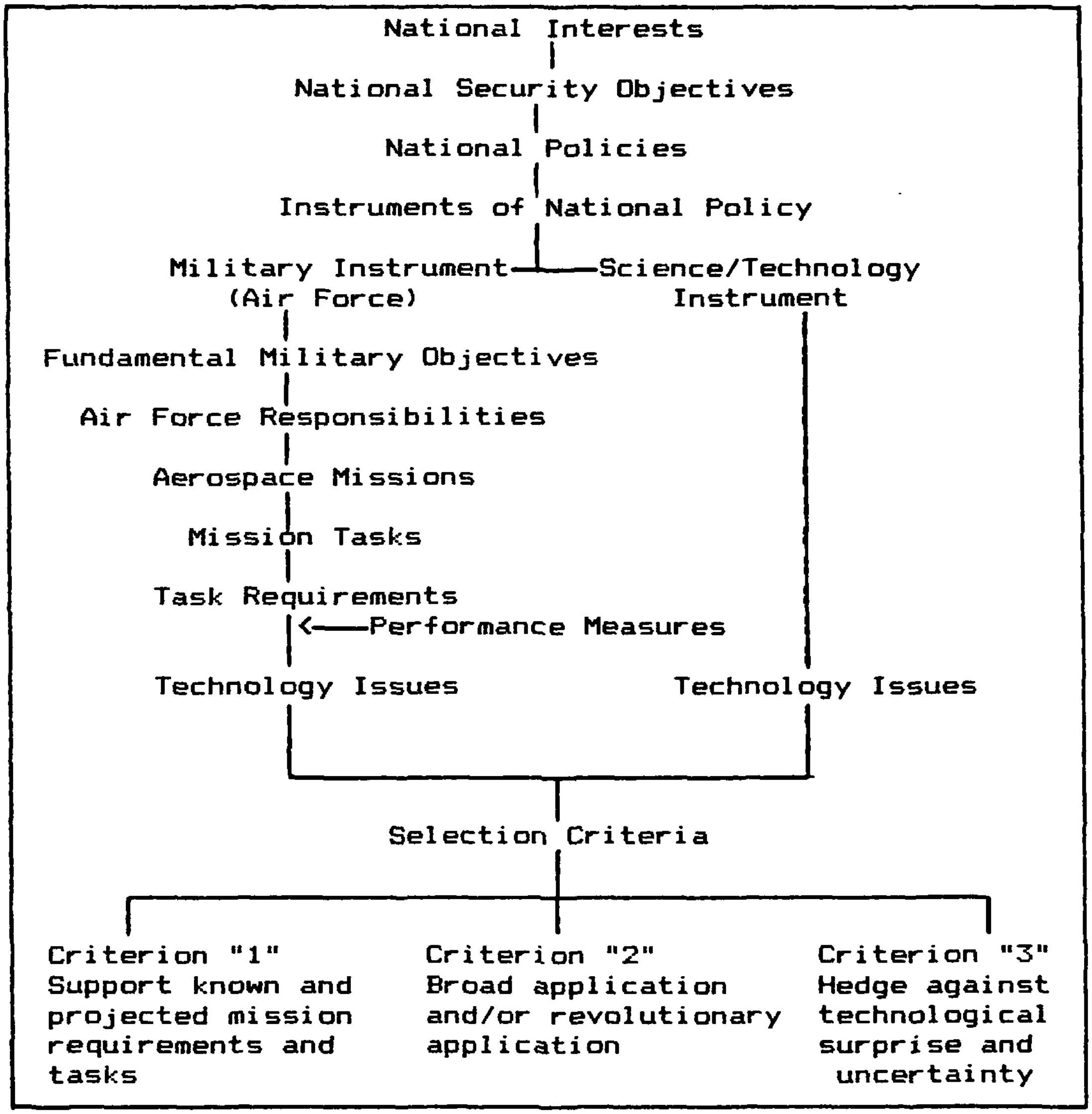

Figure 5-2. Space R&D Advocacy Hierarchy

particular, environmental doctrine seems to have a close interaction with R&D. At times environmental doctrine is proposed on the basis of new technology, while at other times environmental doctrine will challenge the R&D community to provide new capabilities called for by the doctrine. These interactions are not adequately represented from a

mission area analysis alone. The direct linkage between technology issues and the scientific-technological instrument is designed to provide an alternative perspective for evaluating space technology issues that may not readily connect through the mission needs branch of the hierarchy.

Finally, the third change is that we identify three criteria for evaluating the various technology issues' contributions to the hierarchical branches. A decision maker's subjective preferences can be elicited with respect to how technology issues compare using these criteria. The hierarchy linking technology issues to higher level needs is the conceptual and contextual framework within which these comparisons can be made. We also discuss the dynamic nature of these criteria to show that their relative importance could change with respect to time. The criteria we introduce are: 1) supports known and projected mission requirements and tasks; 2) broad application and/or revolutionary application; and 3) hedge against technological surprise and uncertainty.

In the following sections we describe the various levels of our hierarchy. We first cover the levels at and above the military and scientific-technological instruments of national policy and describe the applicability of both instruments to these higher level elements. We then address our mission needs hierarchy and emphasize the differences and the similarities to the MSSTP structure. Next, we describe the technology issue linkage to the scientific-

technological instrument. In both cases we discuss how technology issues are or can be generated from this model. Finally, we discuss the three criteria for evaluating technology issues and provide rationale for selecting these three.

Definitions and descriptions of the hierarchical levels are generally aggregates derived from Air Force policy, published doctrine, the MSSTP, our own thoughts, and a variety of other sources. We point out here that the intent is to justify the various levels of the hierarchy and not the individual elements that comprise each level. While we include descriptions of some of the elements for illustrative purposes, we do not intend to defend the elements shown as a comprehensive or mutually exclusive list.

Upper Levels of the Hierarchy. In this section we describe the levels and interactions between the higher levels of the hierarchy. These levels are national interests, national objectives, national policies, and instruments of national power.

National Interests. National interests are broadly stated representations of basic national values and beliefs. They are fundamental to national survival and the preservation of our way of life with our value systems intact. The elements include preservation of national survival, territorial integrity, economic well-being, and favorable world order. While perceptions may differ on how best to maintain national interests, these elements are not

prone to change over time. National interests drive broadly stated objectives that support national interests.

National Objectives. National objectives provide general guidance on how to maintain or achieve national interests. Elements include security, economic, social, and technological objectives. Our primary national security objective is to preserve the United States as a free nation with its fundamental institutions and values intact. Specific elements of this objective include ensuring the capability to deter attacks, defeat attacks, prevent coercion, limit Soviet advantages, assure access to and through the open seas and space, protect economic interests, contain Soviet expansionism, discourage subversion and terrorism, and foster long-term changes favorable to the United States.

Likewise, national technological objectives support national interests. The primary technological objective is to maintain the superiority of American technology necessary to support national interests. Elements include: maintain technological edge in defense systems, maintain the supremacy of American technology in world markets, and pursue new technologies that expand the boundaries of science and technology.

Space objectives are incorporated under national security objectives and technological objectives. Elements include: maintain US space leadership and cooperate with other nations in maintaining freedom of space for the welfare and security of mankind.

National objectives provide the focus for and shape national policies.

National Policies. National policies are broadly stated but are more specific guidelines to achieve national security and other national objectives. For example, national defense policies represent a "broad course of action adopted by the US government in pursuit of our national security objectives" [7]. Policies reflect the decisions of the national leadership that support national objectives. These policies are constrained by the Constitution, federal and international law, treaties, mutual defense agreements, and other external factors that can impact the decision making process. Policies are more dynamic in that they reflect the current position and beliefs of the national leadership and can vary with changes in the national leadership and the international environment.

For example, space policy is currently constrained by international law and treaty obligations. The U.S. is prohibited by international law and treaties from testing nuclear weapons and deploying weapons of mass destruction in space. U.S. obligations to the ABM Treaty preclude the development, testing, and deployment of space-based ABM systems [210:4].

National space policy guides the civil and military sectors toward national objectives. Examples of national space policy that relate to national technological objectives are: preserve the US preeminence in critical space

activities to enable continued exploitation and exploration of space; continue to explore the requirements, operational concepts, and technology associated with permanent space facilities; conduct appropriate research and experimentation in advanced technology and systems to provide a basis for future civil applications; and develop, manage, and operate a Space Transportation System [8:3]. Space policies that support national security objectives include: pursue surviv-able and endurable space systems that support national security objectives; develop an anti-satellite capability to deter threats to US space assets; and "develop and maintain an integrated attack warning, notification, verification, and contingency reaction capability which can effectively detect and react to threats to United States space systems" [8:3].

National policies are accomplished or pursued by instruments of national power.

<u>Instruments of National Power</u>. Policies are carried out through the use of instruments of national power. These instruments are political, economic, psycho-social, scientific-technological, and military. The ability to pursue national policies is directly dependent on the strengths and capabilities of the instruments of national power. Here our specific concern is with the military and scientific-technological instruments of national power.

The military instrument must be strong enough to sup-port national security objectives as specified by national

policy. The national leadership determines if, when, and how the military instrument is applied, and how it is to be used in concert with other instruments of national power. Since our primary purpose is to link space R&D requirements to national needs, our focus is on how R&D can support the military instrument. Therefore, wherever official guidance suggests that R&D efforts support operational requirements, both current and projected, the R&D issues are indeed linked to national needs through the military instrument.

On the other hand, where guidance relates to maintaining technological superiority (broadly stated, with no direct connectivity to existing or planned systems, capabilities, or military tasks) and hedging against technological surprise, linkage of R&D issues to national interests are through the scientific-technological instrument of national power. This instrument is not as well-defined as the military instrument. However, we describe it as the industrial and technology base represented by American corporations, private and governmental research activities, and educational institutions which provide the skilled people, resources, and innovations necessary to maintain a technological edge [68; 75].

Thus far we have described the higher levels of our hierarchy which represents the framework to identify or consider space technology issues. National issues drive national objectives, which shape national policies. National policies are pursued through instruments of national of

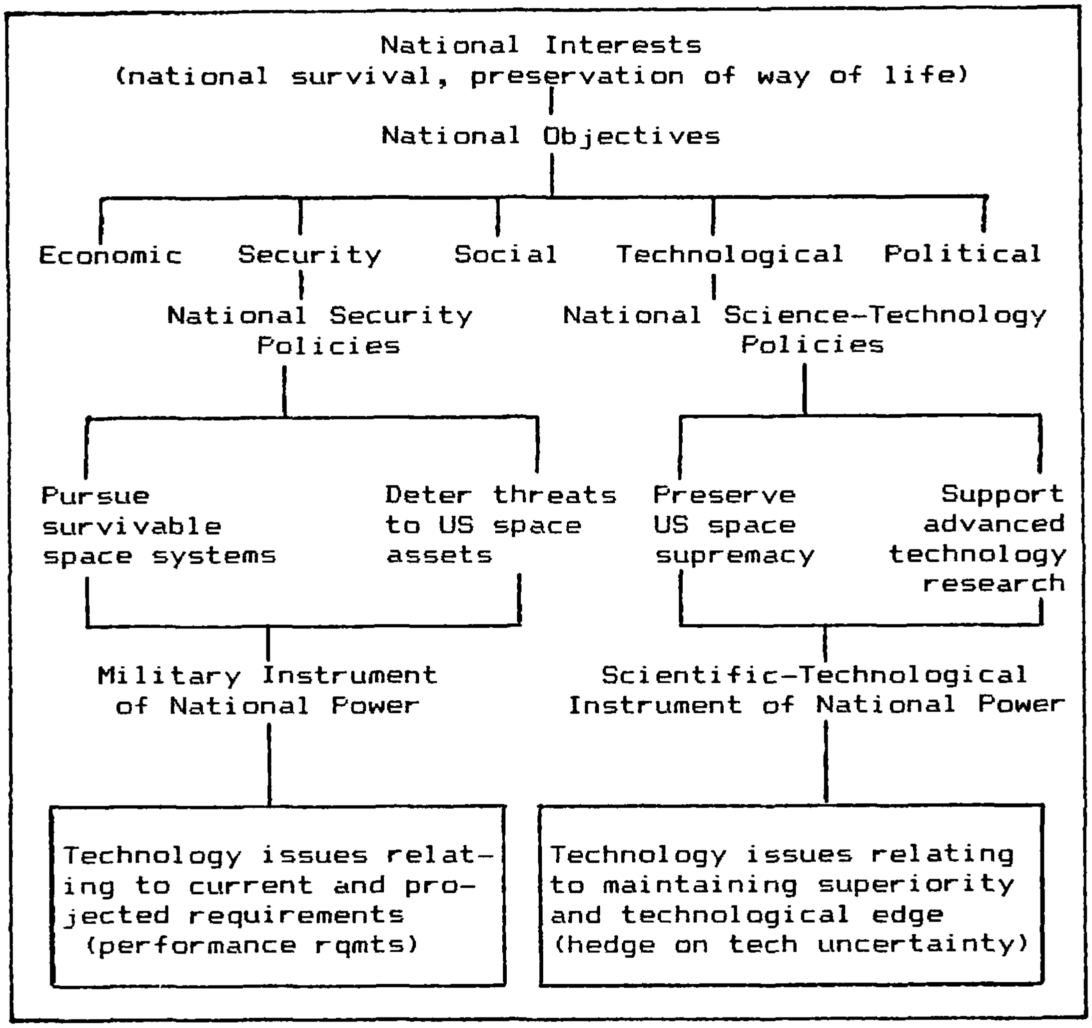

Figure 5-3. Hierarchical Structure, Upper Levels

power. These relationships are shown in Figure 5-3.

The specific connectivity of technology issues to the military and scientific-technological instruments of national power has not yet been shown. We describe these two branches in the sections that follow.

<u>"Mission Needs" Hierarchy</u>. The mission needs hierarchy allows technology issues that relate to military performance requirements to be linked to national interests. This

proposed mission needs hierarchy is very similar to the one described in the MSSTP and TRUMP. However, we have incorporated environmental doctrine in the descriptions of the various levels and elements of this hierarchy. We believe this provides the decision maker greater flexibility in considering potential military tasks that could be accomplished in space, but may currently be prohibited or restricted by policy. As discussed in Chapter Four, the planning horizon for R&D extends well into the future. We can better forecast future military requirements in the context of environmental doctrine, which is relatively unconstrained by current thinking or policy.

The following discussion is an abbreviated description of the levels through which technology issues can be linked to the military instrument and thus to national interests. We expand this discussion in Appendix G, which provides the rationale for our recommended ordering and descriptions of the various levels and elements in the hierarchy. For the sake of brevity they are not addressed here. Our focus is on Air Force requirements, since the Air Force is the DoD Executive Agent for military activities in space. However, our treatment of missions and responsibilities is broadly scoped to include all DoD space-related requirements in this hierarchical model.

Fundamental Military Objective. The military instrument of national power allows the national leadership to pursue national policies in the context of military

operations. The fundamental military objective is to conduct warfare to resolve conflict at all levels on terms favorable to the United States and its allies. Implicit in this objective is that the military instrument must be capable enough to deter aggressive acts detrimental to our national interests. The military must be sufficiently strong and flexible to fight and win at the level of intensity necessary to achieve US objectives.

Air Force Responsibilities. Each of the Armed Services has general functional responsibilites that are assigned by law and policy to support the fundamental military objective. Air Force responsibilities are derived from the National Security Act of 1947, the National Aeronautics and Space Act of 1958, JCS Publication 2, "JCS Unified Action," and DoD Directive 5100.1, "Functions Paper" (1958). The major role of the US Air Force is to conduct aerospace operations in support of the national interests of the United States.

We generated seven Air Force functional responsibilities by rearranging responsibilities listed in AFM 1-1 (1979) and changing descriptions to include the space medium as part of the operational environment. These are:

1. Provide forces to conduct prompt and sustained combat operations in the aerospace to defeat enemy air and space power;

2. Provide forces for strategic aerospace warfare;

3. Provide adequate, timely, and reliable intelligence, surveillance, reconnaissance, and aerospace photography;

4. Provide the capability to interdict enemy targets;

5. Provide forces for aerospace defense of the United States and allied territories and resources;

6. Formulate doctrine and procedures for the organizing, equipping, training and employment of Air Force forces;

7. Coordinate with and support other Services in joint operations and strategy.

Aerospace Missions. Functional responsibilities are supported by various aerospace missions. Until recently, published Air Force doctrine [6] listed nine primary and one collateral missions for the Air Force. Space Operations was defined as one of these missions, with the following three categories: space support, force enhancement, and space defense. To be consistent with our description of environmental doctrine, which asserts that space is part of the operational environment in which Air Force missions are conducted or supported, we developed an alternative list of eight missions. These are: strategic aerospace offense; strategic aerospace defense; aerospace lift support (we included space support, to include launch and recovery of space payloads in this category); close aerospace support; aerospace interdiction; counteraerospace operations (which includes offensive and defensive counter-aerospace missions and defense suppression); special operations; and surveillance and reconnaissance (tactical and strategic).

In Appendix G we define each of these missions and show

how they differ from previously published Air Force doctrine. We note that Air Force doctrine has recently been revised (the draft to AFM 1-1 [7] has been approved) and our mission descriptions are in consonance with this new doctrine. In addition to the changes already discussed, we deleted "force enhancement" as a sub-mission category (previously listed under space operations). Our rationale was that space systems (or any other for that matter) could fully or partially satisfy mission requirements. If they partially satisfy requirements, then they may be perceived as "enhancements", but in reality directly contribute to mission accomplishment.

Mission Tasks. Tasks are defined as those specific capabilities required to accomplish missions. Our task list is similar to the 26 tasks derived in the MSSTP [170], although we have deleted force enhancement type tasks such as "ballistic missile accuracy enhancement." We also restructured tasks to show functional relationships. For example, we show as one task category "detect, identify, track, intercept, and destroy," and list specific types of targets: ballistic missiles/SLBMs, air vehicles, surface (terrestrial based) targets, and space vehicles and platforms. The MSSTP breaks these out differently. For example, task #1 in the MSSTP is "warning of ballistic missile attack on CONUS." Our complete list of tasks is discussed in Appendix G.

We emphasize here that any task breakout is for the

most part arbitrary and subject to several considerations. It is difficult, if not impossible to completely distinguish between elements or even levels in the hierarchy. As we pointed out in our general discussion of hierarchical structures, most real world situations are complex. At best, the hierarchy can only represent a decision maker's perception of real world orderings [213]. The difficulty in discriminating between tasks, between certain tasks and missions, or even tasks and functions (the next level in the hierarchy) is highlighted in the following example.

Consider the task "detect, identify, track, intercept, and destroy manned bombers attacking the United States." In actuality, this is one of the primary missions of the North American Defense Command. And yet the same task, slightly reworded to "detect, identify, track, intercept, and destroy enemy fighter aircraft" is clearly a task in support of the counteraerospace mission.

Our point is that detailed discriminations between missions, tasks, and functions is dependent on the scope and nature of the situation. The decision maker assessing the problem determines the scope and parameters in his evaluation. The hierarchy is still valid as a conceptual framework to structure and evaluate the problem. However, the specific elements may "move" up or down levels on the hierarchy depending on the scope of the problem.

Task Requirements. Task requirements are the basic building blocks or specific capabilities that allow a

task to be accomplished at some required performance level. They help the decision maker further breakout task requirements in terms of functional areas. Our list of task requirements corresponds closely with the fifteen military "functions" discussed in the MSSTP. Again, these elements are to some extent arbitrary, and depend on the scope and nature of the problem under consideration.

Task requirements are specified in terms of various performance parameters. We use the same six described in the MSSTP (area of coverage, capacity, timeliness, quality, survivability, and availability). These qualitative parameters help the decision maker consider the performance levels required of each task requirement.

Technology Issues. Assuming that detailed performance levels can be specified for all required military tasks, then these required performance levels can be matched against available technology. If existing technology will not provide required performance, then a technology issue is defined and quantified by the difference between required and available performance levels necessary to meet task requirements.

Technology issues can also be generated by system concept proposals, "paper studies," expert panels, experimentation, outside sources (industry, independent researchers, etc), and DoD or Air Force planners and operations personnel, either apart from or in conjunction with mission area analyses. Mission area analyses could be easily struc-

tured using the hierarchy we have just described. And if tasks and task requirements were adequately specified, the performance shortfalls themselves provide the best definition for the technology issues that must be resolved to support identified requirements.

We emphasize that our hierarchy does not depend on space system concept studies to generate space technology issues. Concepts are only one of many ways in which technology issues can be identified. We also point out that this recommended structure does not guarantee that all technology issues necessary to support military requirements will be identified. However, we believe it is sufficiently comprehensive to focus attention on the critical issues necessary to provide the broad technology base to meet projected military space requirements.

A major limitation of this or any "mission needs" hierarchy is that it presumes all essential military tasks and requirements to meet future needs can be specified. In Chapter Four we pointed out that there are inherent problems with defining operational requirements for the future. Organizational doctrine, based on current, accepted ways of doing things, limits our perspective and constrains us from considering revolutionary concepts or ideas. While we have attempted to counter this somewhat by incorporating environmental doctrine into our mission needs hierarchy, we recognize that some potentially critical technology issues may still not weight very high when evaluated against a

mission needs hierarchy. In part because of this, we add the linkage of technology issues to the scientific-technological instrument of national power, discussed in the next section.

Linkage of Space Technology Issues to the Scientific-Technological Instrument. An alternative way to consider technology issues is to relate them directly to their relative support of the scientific-technological instrument of national power. This provides a decision maker an alternative approach to considering the potential importance of pursuing certain technology programs that may not rank very high when evaluated against a mission needs perspective.

As pointed out in Chapter Four, some of the most useful and critical technologies used by the military today were not identified by mission area analyses. We pointed out that the airplane, the jet engine, communications satellite, and semi-conductor technologies, among others, were created outside the military environment. Even the inventor of the laser had no idea that his invention would lead to the broad range of applications it has contributed to today. Charles Townes said of his invention "as it turned out, I was much too conservative; the field has developed far beyond my imagination and along paths I could not have foreseen at the time" [254:153]. If past history is any indicator, then it is likely that many of the military technologies of the future may be similarly derived.

We hypothesize that this linkage provides an ideal

perspective to consider technologies that, for one reason or another, may be discounted in a mission needs analysis. Environmental doctrinalists, purporting new military capabilities and tasks that run counter to current thinking, may generate technology requirements that cannot, for political reasons, be considered in a mission needs context. Technologies that cannot be directly linked to existing military needs but, in the mind of the decision maker, could provide tremendous benefits or hedge against technological surprise, could be considered by evaluating their contribution to the broader scientific-technological instrument of national power.

Additionally, sometimes it is worthwhile to pursue research for research's sake. In doing so, we gradually reduce the uncertainty surrounding previously unexplored mysteries. From basic research, with no particular applied technological goal in mind, surface some of the more spectacular discoveries which are later incorporated into military technological applications. Basic research in quantum physics led directly to the development of the atomic bomb, an event clearly unforeseen by the early theoreticians, who had difficulty even accepting the results of their findings, they were so revolutionary. The space technology advocate, aware of basic research proposals, may want to consider these in his advocacy position. The scientific-technological linkage clearly allows him to do so.

In general, while it is extremely difficult to do any

more than qualitatively and sometimes vaguely describe these potential breakthroughs, hedges against technological uncertainty or technological surprise, it is important that the decision maker consider them. For this reason, we show the linkage of technology issues to the scientific-technological instrument.

Additionally, the space technology advocate may want to consider potential benefits of military related space R&D to other national needs. On the other hand, he may also want to speculate on potential military applications for R&D programs underway in the private sector designed to meet commericial needs. This linkage provides a means for doing both.

Technology issues linked to the scientific-technological instrument of national power can be generated in a number of ways. However, they most likely will come from research proposals, "paper studies," or far-thinking theoreticians.

Determining the Strategic and Technical Utility of Space Technology Issues

Up to this point we have described a hierarchical model which forms a conceptual and contextual framework which the space technology advocate can use to link space technology issues to national interests. However, effective space technology advocacy relies heavily on the willingness and ability of the space technology advocate to undertake an analysis of the strategic and technical merits of space

technology issues. We have developed criteria that we feel will focus this analysis. The criteria can be applied to gain insight into the relative importance of technology issues.

The development in the following discussion is broken into two sections. The first section is a discussion of the time frame or planning horizon for technology issue assessment. The second section deals with the criteria for evaluating the strategic and technical utility of space technology issues. We hypothesize that the relative importance of the criteria in this category will change depending upon the time frame. In other words, the planning horizon dominates the strategic and technical utility criteria.

<u>The Planning Horizon</u>. A logical breakout to address this "time dependency" is to separate technology issues by technology due date. This technology due date can fall into four main time categories: present-term, near-term, mid-term, and far-term. The strategic and technical utility criteria should not change in any given time frame. However, the weighting of each of these criteria should and probably will change based upon the time reference for the specific technology issues at hand.

We suggest the following time divisions. The present-term represents technology due dates within the current five-year plan. We assume that technology issues within this time frame are already being addressed by the appropriate advocates (example; System Program Offices).

The near-term is defined as technology due dates that are between 5 and 10 years from the current time. The mid-term would then be the next 5 year period. The far-term horizon represents technology due dates greater than 15 years from the current date. For the year 1985 the present-term is 1985-1990, the near-term is 1991-1995, mid-term is 1996-2000, and the far-term is 2001 and beyond.

We note that near-term planning is more concrete than far-term planning. Mid-term planning naturally falls somewhere in-between. Basically, the near-term deals with specific, possibly well-defined systems whereas the far-term may deal only in hypothetical system concepts. The near term is characterized by actual hardware with heavy emphasis on development whereas the far term can be characterized by "paper studies" and a high degree of uncertainty. The far-term emphasis is on research.

While this suggested breakout of the planning horizon is rather arbitrary, it is logically based and easy to apply. We selected 5 year periods since the Services program in 5 year increments (5 Year Defense Planning, Programming, and Budgeting Cycle). However, there are alternative ways to divide the planning horizon.

<u>The Criteria</u>. With the planning horizon in mind, how do we evaluate the technology issues to determine which are the most important for advocacy? Realistically, the criteria should relate to the overall goal of space technology advocacy. This goal is to provide technology options to

operators and systems developers to meet military space requirements. The R&D process must not only be responsive to current operational requirements, but should also provide technologies that have broad application, that can revolutionize the way we do things in space, and that provide some hedge against the uncertainty of the future. Along these lines we can identify three general reasons for doing R&D. From these three reasons we derive our criteria. The three reasons for doing R&D are [275:34-35]:

> 1. R&D aimed at improvements (enhancements to current capabilities). For example, survivability of satellites may fall here where no performance improvement is made but whereby the satellite can perform its mission for a longer period of time because it is more survivable.
>
> 2. R&D aimed at new capabilities within the context of current tasks. This category provides for "unique" technological advantages in doing current tasks (i.e. do them better by doing them differently). For example, if nuclear intercept of satellites is possible, can the technology be developed to provide successful intercept using strictly conventional warheads/weapons?
>
> 3. R&D aimed at providing new (enabling) capabilities that are beyond the scope of current tasks. In other words, this category gives the capability to do completely new tasks. An example of this would be intercept of ICBM's in their boost phase. This cannot be done today. Within this category are those tasks and requirements that will exist in the future but are as yet unidentified and unspecified.

The technology issues (and the way we have defined them) can be shown to apply to one or more of the above three reasons for doing R&D. We now identify and explain the three criteria to be used in the analysis of the strategic and technical utility of various space technology issues.

Criterion 1. Provide performance levels necessary to meet the threat and/or projected threat within the space arena. In other words, how far does the technology issue go in supporting known mission requirements and tasks? In some cases this can be quantitatively described. The presence of a shortfall in performance level would indicate the existence of one or more technology issues. This criterion allows the decision maker to compare two technology issues in the context of how important is one to the other in terms of the quality provided by the technology issues to the successful accomplishments of military tasks. This assessment would be partly based on the application of these technology issues to various military functions and tasks and to the relative importance of the these functions and tasks to each other. The relative importance of functions, tasks, and missions can be derived in several fashions.

First, mission area analysis from DoD, the Air Staff, and MAJCOM's can aid the decision maker in making the assessment. Also, policy statements from national leaders, both civilian and military, can give the decision maker some insight into the relative importance of various missions and tasks. Other sources for this information are the planning documents that exist within DoD and the Air Force. Finally, the knowledge and experience of the decision maker is, in the end, the most important source of information and judgment for making the assessment.

It is important to note that technology importance can,

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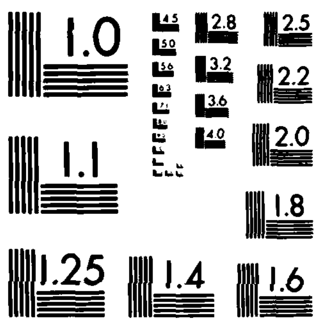

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in one sense, be based on providing a "significant" advantage over possible adversaries. The first criterion encompasses this assessment of a technology issue in terms of providing a significant advantage. However, a significant advantage may only be a marginal advantage in performance level in a given technology issue vis-a-vis the threat. The word significant in no way necessarily implies a major improvement in a technology area. In fact, the exploitation of small advantages or differences in technology within actual weapon systems can be decisive [187:30]. Moreover, a great deal of space R&D will be pursued to provide marginal improvements to existing capabilities.

There is some danger in using this criterion and evaluating space technology issues strictly in terms of the percent of "possible" mission area support that could be provided by the technology issues. The decision maker must be aware of some of these shortfalls. Recall that TRUMP relied upon mission area analysis and developed a mission requirement/concept/project ranking. Some widely recognized problems with this type of analysis are identified by Smith [226:2] and listed below:

1. Ranking of mission requirements is arbitrary (everybody has a different ranking).

2. Fledgling new technologies that could inspire radically new system concepts are handicapped (20 years ago, would lasers have been funded using mission ranking?).

3. Differing likelihoods of being able to implement system "concepts" are not considered (technology development money could be wasted on pipe

dreams).

4. Allocation by rank is sequential and piecemeal.

We add a fifth pitfall. Mission requirements often are specified in great detail before the military is given a chance to discover the true nature of the operating environment. This may be particularly true for the space environment. We can easily link this back to the need to develop the environmental doctrine for space and, from that, define space mission requirements better.

Again, the first criterion is important but not the only consideration when developing a strategy for space technology advocacy. This leads directly to the next criterion which addresses some of the shortfalls described above.

Criterion 2. Provide alternative applications to meet many military tasks. In other words, what is the potential for exploiting the technology issue. As pointed out above, this is a good criterion to weight those fledgling technologies that may have application to as yet unidentified tasks and to allow us to do current tasks in new and unexpected ways.

Let's take a look at laser technology, for example. Not only does the laser have application in the future as a weapon but it also has applications in laser-gyros, laser range-finders, laser target designators, not to mention the hundreds of civilian applications of the laser. However, many of these applications could not be forecast twenty

years ago. But most researchers knew there was great promise although not yet identified. In other words, a laser technology issue may be robust in the number of possible applications that can flow from it. Some of these applications may not be recognizable or have been identified until well after the maturity of the technology. However, in many cases the applications that have been identified are only the tip of the iceberg.

This second criterion is partially redundant with the first criterion. However, this criterion relates more to the potential application of the technology issue. One good example of this is communications issues. These issues will show up in practically any system concept. However, whether or not the communication performance level addressed by the technology issue is truly of higher quality than another technology issue is addressed using the first criterion.

Again, criterion 1 relates to the quality of the technology issue as it relates to the importance of military functions, tasks, and missions in the context of doing these missions in the space arena. The second criterion refers to the potential breadth of application of the technology issue and not only to tasks performed in space but also to other arenas. For example, an ion propulsion technology issue would represent, if resolved successfully, a tremendous improvement in doing certain space tasks. Moreover, it would be hard to imagine an ion propulsion technology issue having broad application outside the realm of space. How-

ever, a communication issue probably would have broad application to all arenas. The "quality" of the communication issue and the ion-propulsion issue may not be the same in the context of overall improvements to space capabilities.

Obviously, in an advocacy position, being able to link space technology issues to other applications besides space can be an aid in gaining support from other non-space advocates and decision makers. Combined support and advocacy can only strengthen the decision makers bargaining power when it comes to the budget process. The intent in these criteria is to derive the "worth" of technology issues. The intent of advocacy is not to get "control" of the programs. Moreover, some decentralization of control of the R&D process leads to a more robust technology base [118:243]. However, a final criterion is needed to address the uncertainty inherent in mission requirement identification and performance specifications, threat projections and R&D processes.

Criterion 3. Provide a "hedge" against technological surprise and uncertainty. A good example for this is again the SDI initiative. One reason for pursuing R&D programs in this area is to be capable of responding to a Soviet breakout from the ABM treaty. An unanswered technology breakthrough in this area could be "catastrophic" for the defense and security of the United States (see [47] for further discussion on the SDI initiative). Also, some proposed technology issues within SDI are highly uncertain as

to their eventual resolution. Hence, these types of technology issues will undoubtedly be rated fairly high under this criterion.

Within this criterion, technology issues can be addressed because of the "lack of research" and as a means of reducing uncertainty. The literature (see chapter two) spends a great deal of time on treating risk and uncertainty in their portfolio selection models. However, one of our hypotheses is that in the space technology advocacy problem the fact that a program or technology issue is high risk and/or uncertain may be a good reason for advocacy. Sometimes the high risk/high payoff technology is the one to pursue in terms of satisfying future, and possibly unidentified, mission requirements. If the goal is to develop those technologies necessary to provide options to meet future mission requirements then it may well be that the high risk project is the only way to get there and, hence, needs to be advocated for that reason. For example, some of the SDI technology issues are important to investigate because their resolution will determine the very feasibility of the concept of BMD. Determining this feasibility will have a major impact on future defense options and will definitely have a tremendous impact on the national budget.

From this description it becomes readily apparent that these three criteria are extremely difficult if not impossible to measure quantitatively. However, the space technology advocate can apply these three criteria subjectively

when evaluating the relative strategic and technical utility of a set of space technology issues. These three criteria are linked directly to the proposed space R&D advocacy hierarchy (Figure 5-2).

The first criterion relates to the "mission needs" hierarchy, linking technology issues through the military instrument of national power to national interests. This criterion deals mainly with the deterministic side of the military technology problem. This side has well defined tasks and possibly well-defined performance characteristics. In other words, the military operators and researchers basically know what they need and have some idea of how to get there.

The last two criteria deal with the uncertainty side of the technology problem. The implications of successful resolution of the technology issue cannot be fully determined given present information. Also, these two criteria cover technology issues that may lead to as yet unidentified military tasks and applications. The space technology program that is advocated must not only address that which we can identify but must also pursue unknown future capabilities and applications. While the "mission needs" hierarchy attempts to consider future needs by taking an environmental doctrine perspective, it may not be completely adequate for covering all possible uncertainties. For this reason, we have expanded the hierarchy to show linkage through the scientific-technological instrument of national power to

national interests. This linkage provides a rational and realistic means to consider the worth of pursuing "research for research's sake" as a hedge against many of the uncertainties of the R&D process.

The purpose of this discussion was to identify and describe a robust set of criteria that can be applied in a worth assessment of a set of space technology issues. The three criteria are robust in that they include not only the well-defined aspects of the mission needs hierarchy but also "hedge" against the uncertainty that is an inherent part of R&D planning. Moreover these three criteria are linked to policy statements, planning documents, Air Force regulations, and Air Force doctrine. The criteria relate directly to the objectives and goals of space technology advocacy and they appear to be those criteria most important to the advocacy process, as they comprehensively address the reasons for doing space R&D.

Conclusion

In this chapter we described a hierarchical model for relating space technology issues to national interests. We showed that the linkages can work up or down the hierarchy. For example, technology issues can be derived from evaluating performance requirements in the mission needs hierarchy. Also, the relationship of technology issues derived externally from the hierarchy can be linked to other elements in the hierarchy. We pointed out that this hierarchy

is a conceptual model that can represent the decision situation of the space technology advocate.

We also described three criteria which can be used to prioritize technology issues based on their relative importance to the three criteria. We indicated that the space technology advocate should evaluate technology issues against these criteria under different planning horizons. This allows flexibility in that technology issues may vary in importance depending on the planning horizon in which they are being considered. We believe these criteria, although broadly defined, will prove useful in prioritizing critical technology issues necessary to support the military space systems of the future. However, a significant drawback is that the criteria are subjective and not necessarily independent. With the possible exception of the first and second criteria, it would be impossible to quantitatively apply them in a worth assessment of space technology issues.

On the surface, it may appear we need go no further in describing a decision support system for prioritizing technology issues. We have described a hierarchical framework which represents a model of reality. We have identified criteria against which candidate technology issues can be weighed. However, we have not defined a methodology for applying these criteria to prioritize technology issues. Additionally, we have not yet described the decision support elements that guide the decision maker in his advocacy role.

In the next chapter we discuss a decision support

implementation plan. It incorporates the criteria we have identified in this chapter with a methodology for eliciting subjective judgments from the decision maker, in conjunction with other information, to formulate a technology worth assessment. The decision maker can consider this assessment, match it against his perception of external factors, and revise his assessment accordingly. The final product, after perhaps several iterations, is the space technology advocacy position. A model of this process is shown in Figure 5-4.

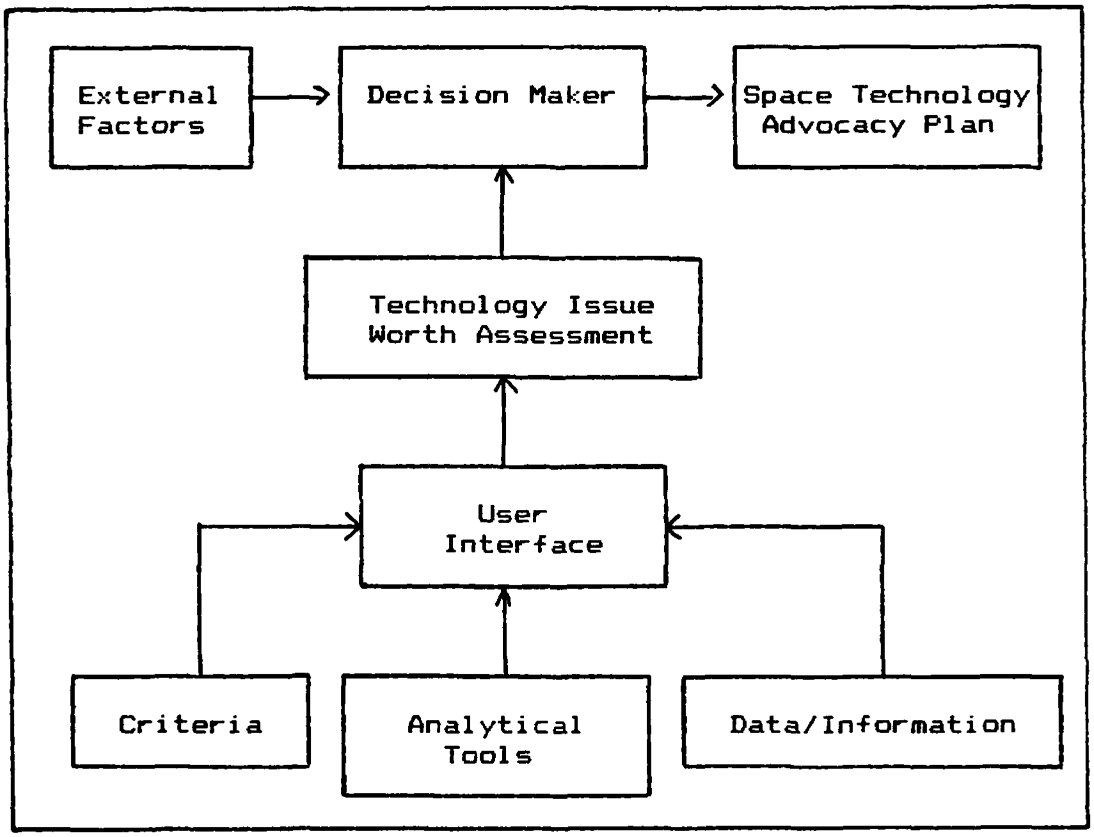

Figure 5-4. Space Technology Advocacy Model

VI. Implementation of the Decision Support Methodology for Space Technology Advocacy

Introduction

The previous chapter described a hierarchical model that linked technology issues to national interests. We also developed three criteria to evaluate technology issues. In this chapter we conclude our description of a decision support model for space technology advocacy. The model considers the criteria and information requirements. These are tied together with an analytical tool through a user interface. Using this model the decision maker can effectively assess the worth of space technology issues. The decision maker then considers this worth assessment in conjunction with external factors (many of which were described in Chapter Four) in developing a space technology plan. This decision support model is shown in Figure 6-1.

We refer to the elements used to derive a technology issue worth assessment as the decision support methodology. We have already discussed the criteria and focus on describing three of the other elements: information requirements, analytical tools, and the user interface.

The first section discusses the information requirements needed to use our proposed methodology. Here we describe the database, database management system, and information required to make technology issue assessments. Our database is a natural extension of the MSSTP database, which already exists. Our proposed methodology recommends a

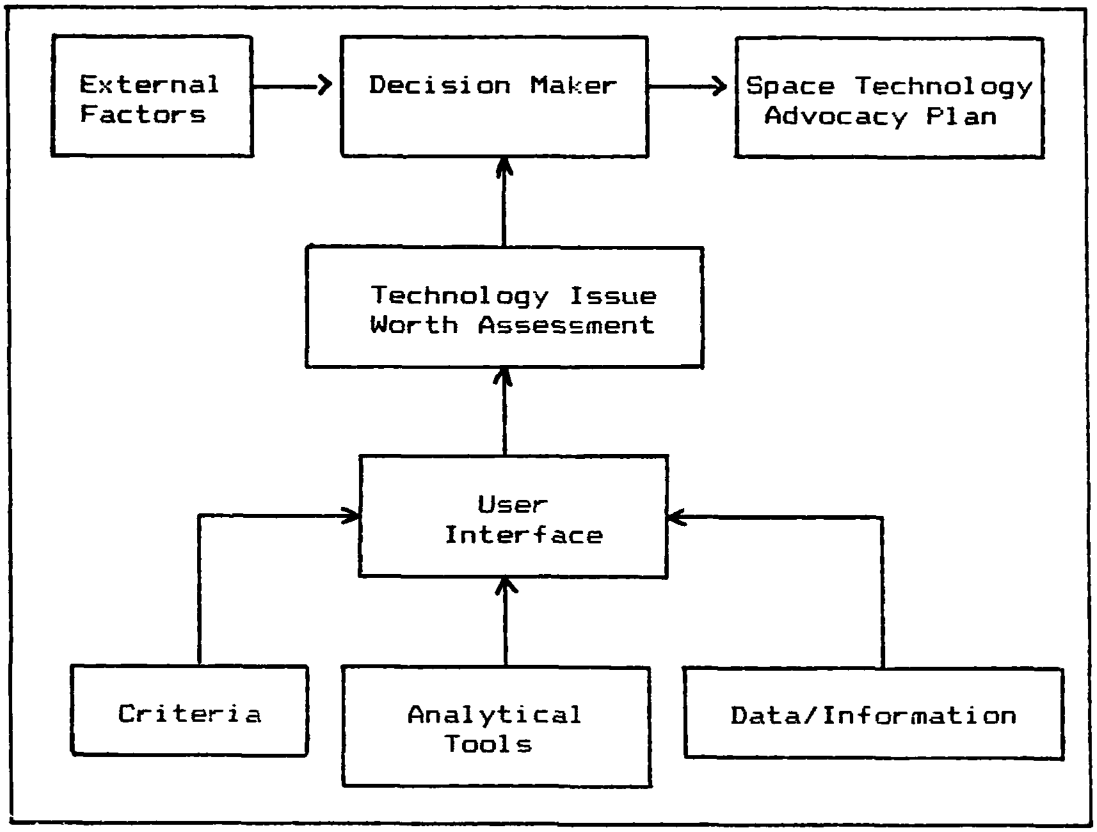

Figure 6-1. Space Technology Advocacy Model

database management system that allows the decision maker to interactively process information from this space technology database. The database and the information in it help focus the decision makers' judgments when evaluating space technology issues.

The second section is a discussion of the analytical element of the decision support model -- the analytic hierarchy process (AHP). The AHP is a multiple criteria decision making (MCDM) technique. As pointed out in Chapter Two, the AHP has many advantages over other MCDM techniques. We use the AHP to elicit subjective assessments of the

various technology issues from the decision maker. A rank/weighted ordering of the technology issues can then be derived based upon each technology issues contribution to the satisfaction of appropriate criteria. We discuss various ways that the results of the technology issue analysis can be interpreted and used to develop a space technology advocacy plan.

The last section in this chapter discusses the user interface. The user interface is addressed in the context of general guidelines for transforming the methodology into a computer-based decision support system for space technology advocacy. The decision support system would then provide the decision maker with a tool for making better decisions.

Information Requirements

> In order for an analysis to provide sound advice it is essential, of course, that the information and data on which it is based be sound. To some extent these can be found in published reports and books or can be gathered by the analyst, but to a large extent it must be found in the minds of experts. Moreover, expert judgment and intuition must be used to interpret it [189:187].

In this section we present the information requirements for this methodology including a preferred database structuring. We describe this database structure within the context of a relational database, which is an improvement over the MSSTP hierarchical database structure used in the MSSTP database. This relational database can be easily manipulated to filter out subsets of technology issues. We

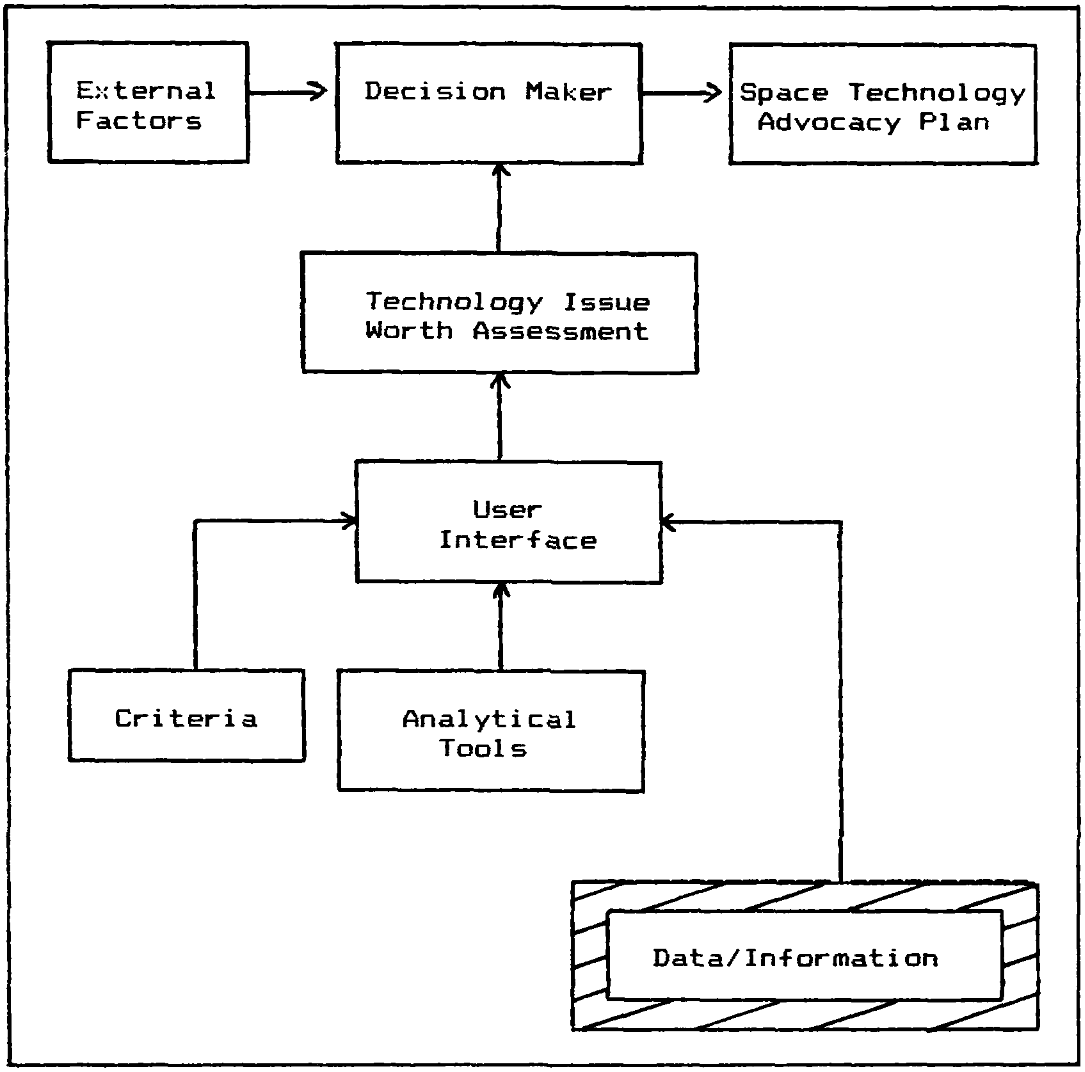

Figure 6-2. Space Technology Advocacy Model Information Requirements

note here that we are describing an ideal lection of information. In actual practice much needed information will not be available and may not even exist.

One of the most difficult steps in gathering information is determining the actual information requirements. Sage [207:152] identifies several methods of determining information requirements [207:152]:

1. Simply ask people for their requirements.

2. Elicit information requirements from existing systems that are similar in nature and purpose to the one in question.

3. Synthesize information requirements from characteristics of the utilizing system. Basically, by determining the types of questions that a decision maker wants to answer you can determine the type of information needed in order to provide the answer to the question.

4. Discover needed items of information by experimentation.

Sage [207:142] goes on to cite several assumptions that can be made about information.

1. The amount of initially available information is usually only a small fraction of what could be available.

2. The economic and other costs of obtaining additional information is often large.

3. Important information, especially that information that pertains to future events, is often incomplete, imprecise, and uncertain.

4. It is important that the information in the database, or otherwise available to the decision maker, not bias the decision maker and that as complete a picture as possible be provided to him.

Data Requirements. In this section we briefly describe the information that should be available to the decision maker. First, we assume that a "list" of technology issues is already available. As pointed out in Chapter 5 these technology issues can be identified in a variety of ways. We also assume that other data is available such as approximate technology requirements and technology availability dates.

The database should also contain information regarding

the number and type of projects currently being budgeted against a particular technology issue (if any exist). Also, technology issue dependencies as well as possibly mutually inclusive and exclusive technology issues should be identified. The original MSSTP database contained information of this type.

The elements of information that should be available to the Space Technology Advocate when assessing/pairwise-comparing technology issues with respect to the criteria are listed below:

-- technology due date

-- technology start date

-- current "funded" programs

-- other advocates

-- concepts that the technology issue could be applied to

-- technology discipline within which the technology issue lies

-- performance figures of merit in terms of current state-of-the-art, projected state-of-the-art

-- DOD executive agent

-- primary laboratory or "actor" that would actually attempt to resolve the technology issue

-- nominal projections of R&D life cycle cost of addressing the technology issue

-- summarized description of the technology issue

-- linkage to the mission needs hierarchy if known

-- intelligence estimates of current and projected threat

-- points of contact

-- sources of additional written information. This could

include DTIC reports, AIAA panel reports, etc.

This type of information should be readily accessible to the Space Technology Advocate when assessing technology issues. For efficient access the information should be available in an organized format. This is easily accomplished using a computer database and database management system.

Database Management. The principal virtue of a database management system is that it frees both the information seeker and the information supplier from any need to understand the complexities of the computer, which allows them to concentrate on the data. In the case of a relational database management system, the structure of the data is compact and hence "large" databases can be integrated into microcomputer applications. For example, assuming 200 technology issues, with 10,000 bytes of information per technology issue (approximately 8 pages of text), the storage requirements would be approximately 2 MegaBytes of memory. This is well below the limit of 10 MegaByte Hard Disk storage media that are currently available for most microcomputers.

There are several ways to organize a database [197]. The MSSTP is organized hierarchically. We recommend a relational database. We now compare these two database structures and highlight the advantage of the relational type.

The hierarchical model [197:53] can be defined as a set of record types with a set of links between record types. All record types have links and to each record there corre-

sponds exactly one other record called the parent. The number of links is restricted to at most one between two record types. Finally, there is a unique record type with no parent record type called the root record type. In other words, the hierarchical model can be represented by a tree structure as illustrated in Figure 6-3. The hierarchical model involves a complicated physical structure with data dependent upon the links that are established within the database. These links take up available memory.

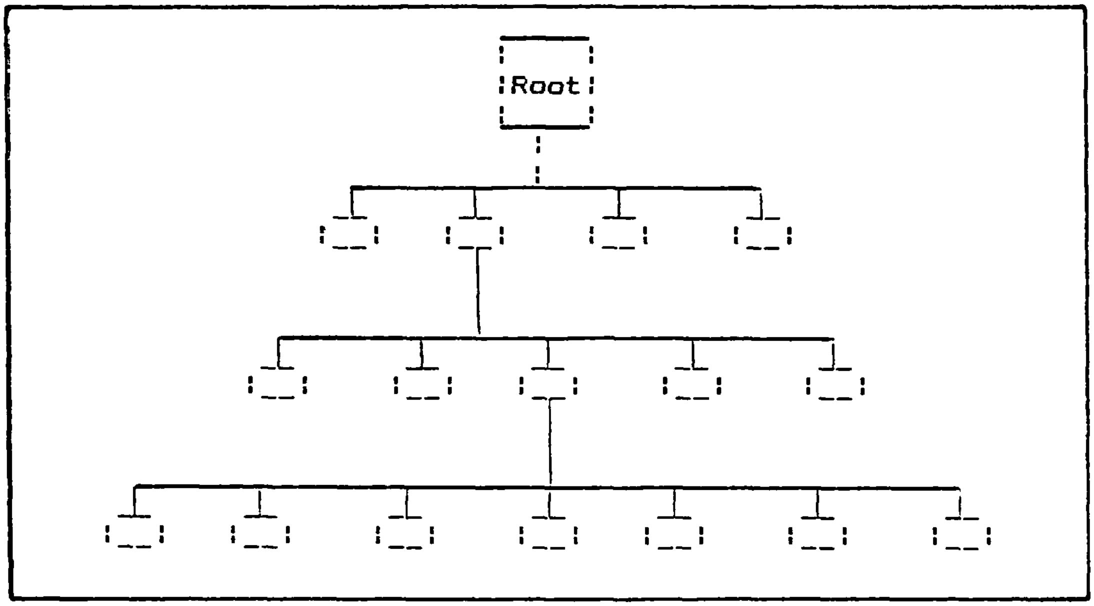

Figure 6-3. Hierarchical Database

On the other hand, a relational database has the advantage of data independence and compactness. The key to using a relational database is in understanding the flat file (which is basically a table of data) and the conditions necessary to call it a relation [197:58]. First, each entry in a relation represents one data item (there are no re-

peating groups). Second, in any column all data items are of the same kind. Third, each column is given a distinct name. Further, all rows are distinct (no duplicate rows are allowed). Finally, both the rows and columns can be viewed in any order at any time without affecting the information content of any function using the table.

A flat file observing these rules is a relation. A column is called an attribute. The flat file representing a record type having columns containing data item values and rows called records becomes a relation. The database can be manipulated by referencing the appropriate attributes. A good example of a relational database is the telephone book.

Figure 6-4 shows a sample relational database. The attributes are technology issue name, the executive agent, the technology start date, and the technology due date.

Technology Issue	Executive Agent	Technology Start Date	Technology Due Date
Autonomous Navigation	USAF	1990	1995
Ionospheric Propagation	DARPA	1986	1991
Data Processing	USAF	1985	1990

Figure 6-4. Relational Database

In effect, if a relational database is built around suitable attributes, sort/search techniques can be applied

in order to scope the problem for the decision maker. The following attributes could be valuable in reducing the scope of the decision situation for the decision maker when he evaluates the various space technology issues: time period, type of research (61xx, etc.), technology discipline, major actors (i.e. labs), technology due date, technology start date, and major mission area.

Besides having sort/search techniques available, the database management system should include algorithms that allow the user to manipulate and analyze the data. One obvious area for this type of application are decisions involving budgetary impacts. Obviously, this requires funding data be made available. However, it is unlikely that all such data will exist and will probably have to be approximated by the experts. An algorithm to do this could include the presentation of simple funding curves to the decision maker or expert. An interactive algorithm then prompts the decision maker to choose the most likely shape of the funding curve as well as to specify nominal time and budget figures. The algorithm can then calculate a yearly budget requirement and this then can be used to assess decisions in terms of budgetary impact. However, the decision maker should be cautioned that this type of analysis tends to be inaccurate due to the highly uncertain nature of the problem. Hence, wrong conclusions can easily be made. Appendix H shows a simple example of this algorithm.

The key points here are that the database management

algorithms should be flexible enough to address many different subsets of technology issues, and should allow the user to manipulate the data so he can address his decision situation with the best available information.

The next section presents the analytic hierarchy process and how it is used to apply the planning horizons and the criteria in order to prioritize technology issues as part of the space technology advocacy strategy.

The Analytic Hierarchy Process

> Expert opinion must be called on whenever it becomes necessary to choose among several alternative courses of action in the absence of an accepted body of theoretical knowledge that would clearly single out one course as the preferred alternative [189:187].

The analytic hierarchy process (AHP) is the multiple criteria decision making technique (the analytic tool in Figure 6-5) we have chosen to elicit the subjective preferences of the space technology experts and as the way in which to prioritize technology issues. The technology issues are prioritized by the technology advocate and/or his staff according to the three criteria discussed in the previous chapter. This section discusses the AHP technique in general and shows how it can be used in the overall space technology advocacy methodology.

The analytic hierarchy modeling and measurement process developed by Saaty [198; 200; 202; 203] is a recent addition to the many approaches used to determine the relative importance of a set of activities or criteria [280:641].

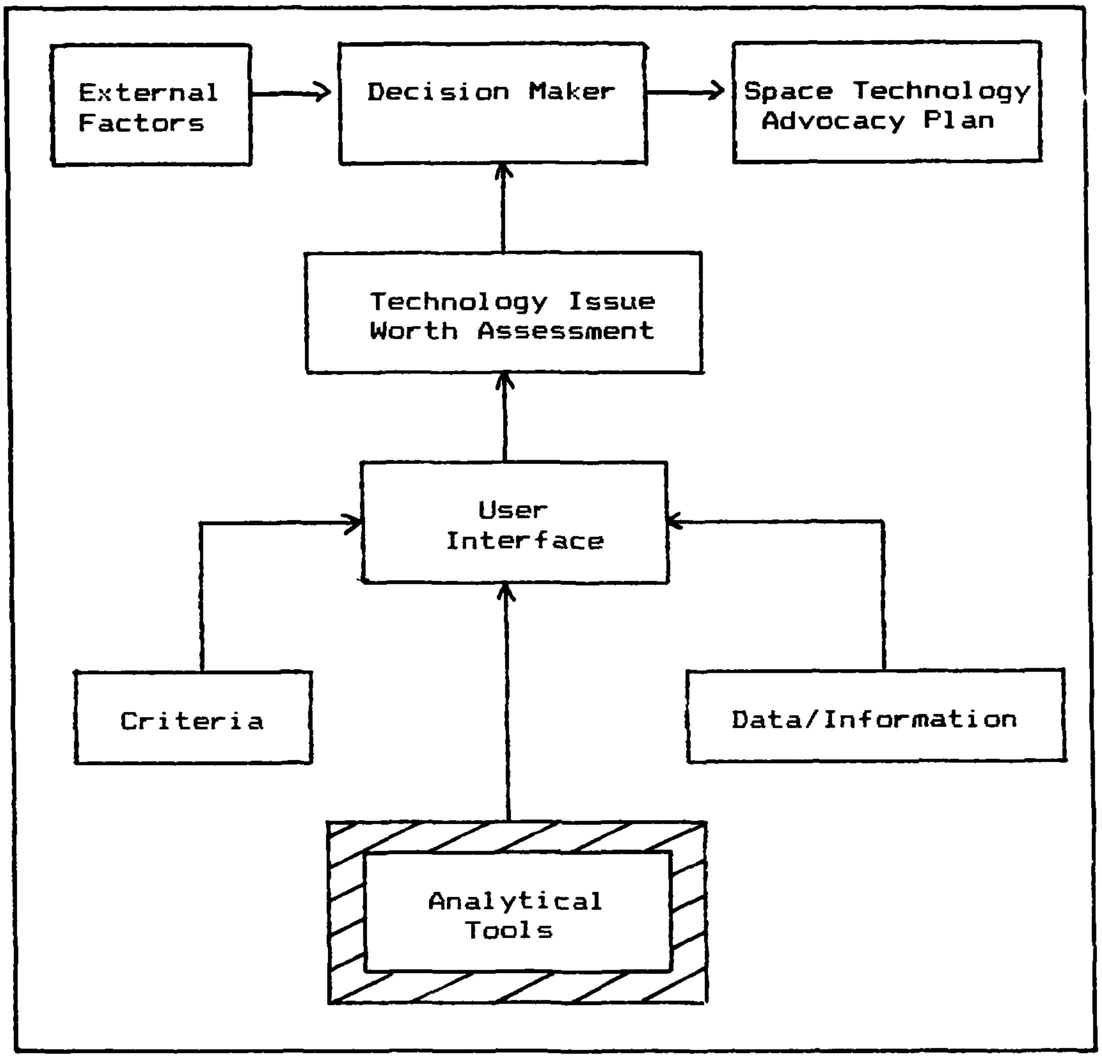

Figure 6-5. Space Technology Advocacy Model Analytical Tools

Its uniqueness is that it can be used to structure hierarchically any complex, multicriteria, and multiperiod problem. However, for the space technology advocacy problem, the most valuable aspect of the AHP is that it easily handles intangibles. "The AHP provides a comprehensive framework to cope with the intuitive, the rational, and the irrational... [202:141]." As such, it provides an excellent

mechanism to elicit the subjective judgments of experts as these judgments pertain to the prioritization of space technology issues.

Since we are concerned with a decision maker's preference for technology issues, we must have a model which provides for and can deal with subjective inputs. The AHP provides a nice tool for this and is relatively easy to learn and to use.

In the space technology advocacy problem, the process of judgment involves making pairwise comparisons between technology issues according to a given criterion [2:94]. The AHP allows the decision maker to do this by breaking the problem into three stages. First, the problem is decomposed into a hierarchy (see Figure 6-6) with each level consisting of a few manageable elements. Second, the elements of the hierarchy are assessed or prioritized by using the nine point scale shown in Figure 6-7. Third, all the priorities are pulled together through the "principle of hierarchical composition" to provide the overall assessment of the technology issues [198:5; 203:1; 266:61]. It is important to note that structuring a problem hierarchically can be considered an art since there is no "one best way" of hierarchical structuring [266:61]. In our case, we have constructed a relatively simple hierarchy without the participation of the decision maker. We feel this is a weakness in the approach (the decision maker should be involved in developing the hierarchy) and not necessarily in the valid-

ity of the hierarchy. The hierarchy that we actually used in testing the methodology (Chapter 7) is presented in Figure 6-6.

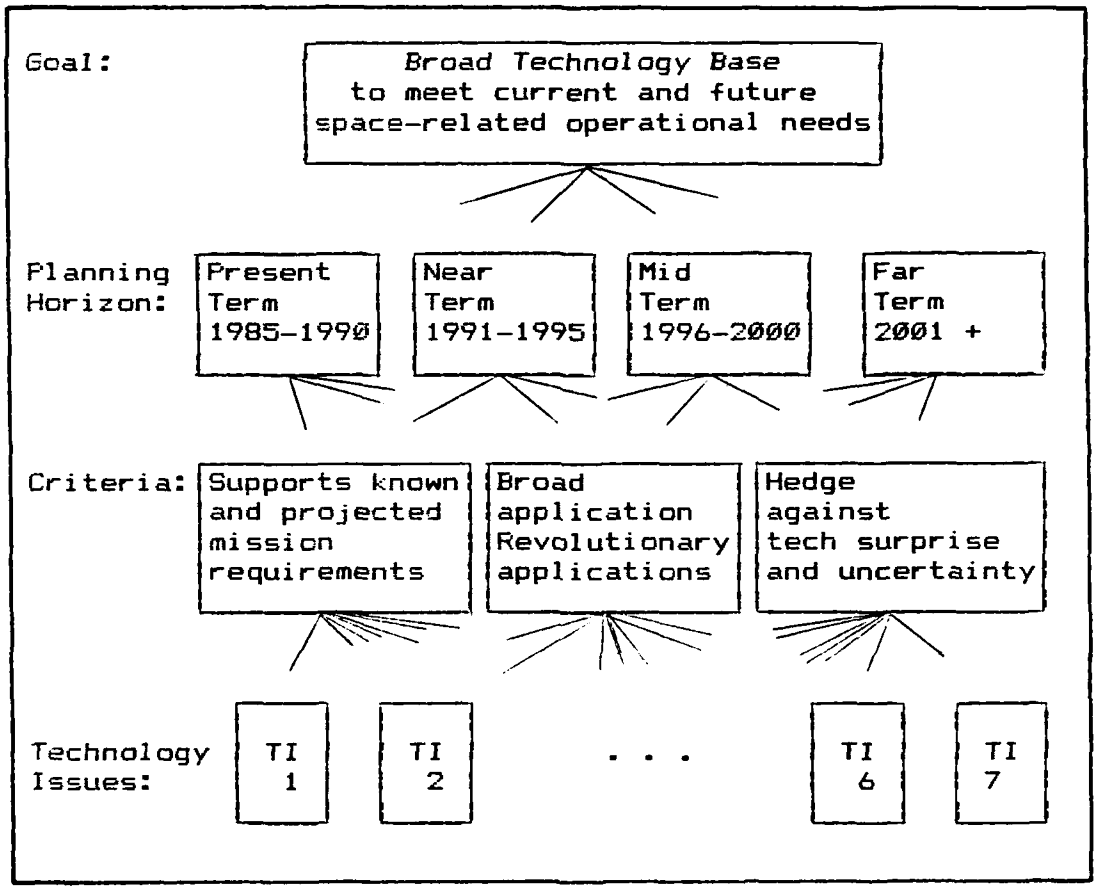

Figure 6-6. AHP Hierarchy for Technology Assessment

We now summarize the steps of the Analytic Hierarchy Process. These steps are taken from the following sources: [202:142; 266:68; 280:646].

Step 1: Define the problem and determine what you want to know.

Step 2: Structure the hierarchy from the top (the objectives from a general viewpoint) through the intermediate levels (criteria on which subsequent levels depend) to the lowest level (which in our case is the list of the technology issues in

question).

Step 3: Construct a set of pairwise comparison matrices for each of the lower levels -- one matrix for each element in the level immediately above. An element in the higher level is said to be a governing element for those in the lower level since it contributes to it or affects it. *In a complete simple hierarchy, every element in* the lower level affects every element in the upper level. The elements in the lower level are then compared to each other based on their effect on the governing element above. This yields a square matrix of judgments. The pairwise comparisons are done in terms of which element dominates another. These judgments are then expressed as integers (see table below). If element A dominates over element B, then the whole number integer is entered in row A, column B and the reciprocal (fraction) is entered in row B, column A. Of course, if element B dominates element A then the reverse occurs. The whole number is then placed in the B,A position with the reciprocal automatically being assigned to the A,B position. If the elements being compared are equal, a one is assigned to both positions.

Step 4: There are $n(n-1)/2$ judgments required to develop the set of matrices in step 3 (remember, reciprocals are automatically assigned in each pairwise comparison).

Step 5: Having made all the pairwise comparisons and entered the data, the consistency index is computed using the eigenvalue. This index gives a measure of the decision maker's consistency in his pairwise comparisons.

Step 6: Steps 3, 4, and 5 are performed for all levels and clusters in the hierarchy.

Step 7: Hierarchical composition is now used to weight the eigenvectors by the weights of the criteria and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy.

Step 8: The consistency of the entire hierarchy is found by multiplying each consistency index by the priority of the corresponding criterion and adding them together. The result is then divided by the same type of expression using the random consistency index corresponding to the dimensions

of each matrix weighted by the priorities as before. Note first that the consistency ratio should be about 10 percent or less to be acceptable. If not, the quality of the judgments should be improved, perhaps by revising the manner in which questions are asked in making the pairwise comparisons. If this should fail to improve consistency, then it is likely that the problem should be more accurately structured; that is, grouping similar elements under more meaningful criteria. A return to Step 2 would be required, although only the problematic parts of the hierarchy may need revision.

Appendix I describes the actual mathematical calculations required in the AHP.

The process of eigenvector extraction and hierarchical weighting and composition leads to a unidimensional scale for the properties of the elements in any level of the hierarchy. The resulting technology issue priorities represent the intensity of the respondents' judgments as to the relative importance of the technology issues represented in the hierarchy considering the importance of and tradeoff among the criteria. In any case, these priorities depend on subjective preference and judgment [119:156]. The AHP produces a single quantitative measure for each criterion for the purpose of prioritizing the technology issues. The relative weights obtained through the AHP can then be used to develop a rational space technology advocacy plan.

We assume that the appropriate forum for space technology assessment is expert groups. The AHP is also an effective tool in a group setting. The next section discusses the use of the analytic hierachy process in the context of group problem solving.

Scale of Relative Importance used in the AHP

Intensity of Relative Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Slight importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above non-zero numbers	If an activity has one of the above numbers assigned to it when compared with a second activity, then the second activity has the reciprocal value when compared to the first.	

Figure 6-7. AHP Scale of Relative Importance

Group Problem Solving using this Methodology.

When dealing with a multi-faceted problem with the aid of a variety of experts of different backgrounds, perhaps the most important requirement in the interest of an efficient use of these

> experts is to provide an effective means of communication among them. Since each of the participating experts is likely to have his own specialized terminology, a conceptual alignment and a real agreement as to the identity of the problem may not be easy to achieve, and it becomes almost imperative to construct a common frame of reference in order to promote a unified collaborative effort (Olaf Helmer in "The Systematic Use of Expert Judgment in Operations Research" as quoted in [189:190]).

We do not assume that a single decision maker will be able to realistically assess hundreds of technology issues. In fact, this methodology is well-suited for, and should be used by, expert groups in assessing the strategic and technical utility of selected subsets of space technology issues. This section describes some aspects of group problem solving in the context of using the AHP as an analytical tool to assess space technology issues.

First, a short discussion of the composition of the expert groups is necessary. An example is probably the best way to show the expertise required to use this methodology effectively to assess technology issues.

Assume that communication issues are to be prioritized. The group should consist of communication experts that have a broad background in the communication field, i.e. communication technologists. Also, included in this group should be military officers well-versed in the military aspects of communication. Hence, the group is composed of technical experts and military experts. In a sense, this group is composed of specialists and generalists. As Quade [189:187] states "the specialists provide substantive information and

prediction, whereas the generalists offer problem formulation, model structuring, or preference evaluation among the predicted alternatives."

The exact size of the group is not so important as long as the participants have shared goals, intimate long term contact and work in a climate of social acceptance with each member having equal status when participating [203:31]. However, the number probably should not be less than five nor more than twelve members. This is the "ideal" group composition [108]. If the ideal group cannot be assembled then it is paramount that the group leader ensure that the group remains focused on the issues at hand and that all questions are specific and interpreted the same way by all group members.

The use of the AHP in this group setting is an adaptation of Saaty [198; 202; 203] and Lockett, et. al. [155] and Gear, et. al [96]. Basically, the technique is the Delphi method or nominal group technique coupled with the AHP. The Delphi method would be used when the group cannot get together. The nominal group technique is appropriate when the group members can physically get together. This technique allows the individuals in the group to have the benefit of the AHP methodology including the measure of inconsistency. By each individual providing separate information it is possible to better utilize the experience of the group and provide a mechanism for articulation of subjective estimates of the relative worth of the technology

issues.

A word picture of the group process is presented below. Appendix J presents additional mathematical and statistical elements that can used with the AHP in a group setting.

The group of experts would first be educated in the AHP technique by presenting them with an outline of the method, including those parts applicable to the group situation. They would then be presented with an example problem to show the flow of the process. Finally, the specific problem at hand is presented along with the proposed AHP hierarchy. A discussion then takes place in order to clarify the hierarchy and the technology issues and criteria. It is at this stage that the activities of separate divisions within the Air Force R&D community can be structured separately, with the aid of the database and the database management system algorithms.

Once agreement has been reached on the form of the problem and the method to be used in the assessment, each individual in the group then goes through the hierarchy and gets a weighted preference for technology issues. Obviously, each member should have access to the information in the database as well as any other technical documents or mission area analyses that might help him make a better informed choice. After this, the group is brought back together and each would receive an "average" group result presented for comparison with their own results. A discussion then takes place about the results, their perceptions, and their

differences.

Some simple visual aids would aid the group discussion. For example, a simple histogram and some descriptive statistics can be applied to the members' results. In this way, a visual group assessment is available. Obviously a "tight" histogram with a small variance indicates some degree of consensus. A histogram with a wide variance and an almost uniform distribution of points indicates that more discussion and/or information is needed. For example Figure 6-8 shows a bimodal distribution of pairwise comparisons. In this case there is significant disagreement among group members. Further discussion and additional information may be necessary to ultimately achieve consensus.

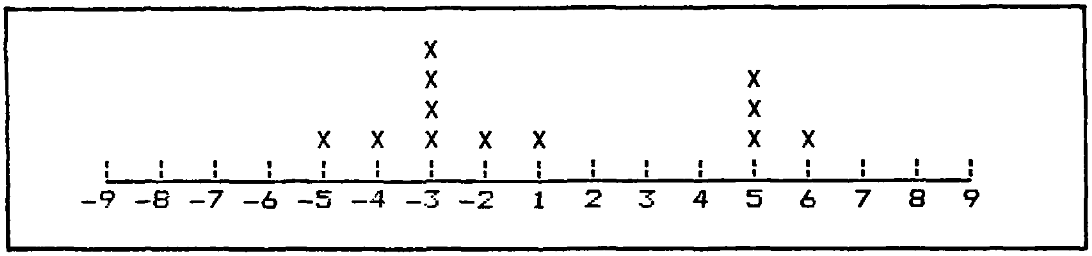

Figure 6-8. Histogram of Pairwise Comparisons

When all members have finished going through all levels of the hierarchy, they are brought back together and given the comparative data. Another group discussion takes place. Following this, either a re-run of the model is in order or possibly a close-down. Hopefully, consensus is reached on the ranking of the technology issues.

During this process each individual's input is monitored so that a complete record is available of their actions.

This is important for later interpretation of results and sensitivity analysis. Also, each individual's analysis is kept from the group during this process so as to reduce group pressure.

Obviously, this process is greatly facilitated by an interactive personal-computer program (We used <u>Expert Choice</u> mentioned previously). The interactive program presents the choices in a pairwise fashion to the expert. The expert then enters his pairwise subjective estimates of the relative worth of each of the technology issues, one to the other. If the problem has been scoped down in size sufficiently, we would recommend that the experts also enter short, free-text explanations justifying their choices. Listings of various experts' documented pairwise comparisons and their explanations provide a very handy method to pin-point differences among the experts [226:10] and as additional summarized information available for addition to the database.

The next section describes the sensitivity analysis that can be applied to the group results.

<u>Sensitivity Analysis</u>.

> The uncertainties of most planning problems can never be completely eliminated [146:57].

> ...implementing a piece of research requires a judgment about the future and how it will be modified by the research findings. The judgment is subject to error, which increases the further one peers into the future. It must be recognized that they are considered judgment, but not necessarily the truth [176:126].

After the decision maker or group of experts have applied the criteria to the subset of technology issues and reviewed the results, it is important that some sensitivity analysis be performed on the final solution. This is necessary to test its stability and to better interpret the solution in the context of imperfect information.

One of the first things the decision maker must determine is the relative stability of his assessment. In this case the weightings for the planning horizons and the weightings for the criteria can be manipulated to check whether or not the final solution is sensitive to small changes in these weightings. If the solution is not sensitive to small or medium changes in these weightings then the decision maker should be more confident in the solution. However, if the solution is unstable then he must perform further analysis in order to increase the confidence in the final solution. This can only be done by gathering further information and redoing the assessment.

Also, the decision maker can test whether or not a particular criterion is important. In other words, if the final weighted priority list shows no significant differentiation between the technology issues under one criterion, then this criterion does not add information and hence can be dropped for that particular set of technology issues. In other words, if all technology issues score about equally with respect to a given criterion, then that criterion will be judged unimportant by most decision makers. Such a

criterion does not help in making a decision [288:187]. Identifying unimportant criteria would also help reduce the time and complexity of further sensitivity analysis.

With better information, some of the individual assessments made in the pairwise comparisons using AHP will probably change. A reassessment will obviously need to be done. The solutions can then be compared to determine whether or not the priorities and rankings of the technology issues have changed and by how much.

<u>User Interface</u>

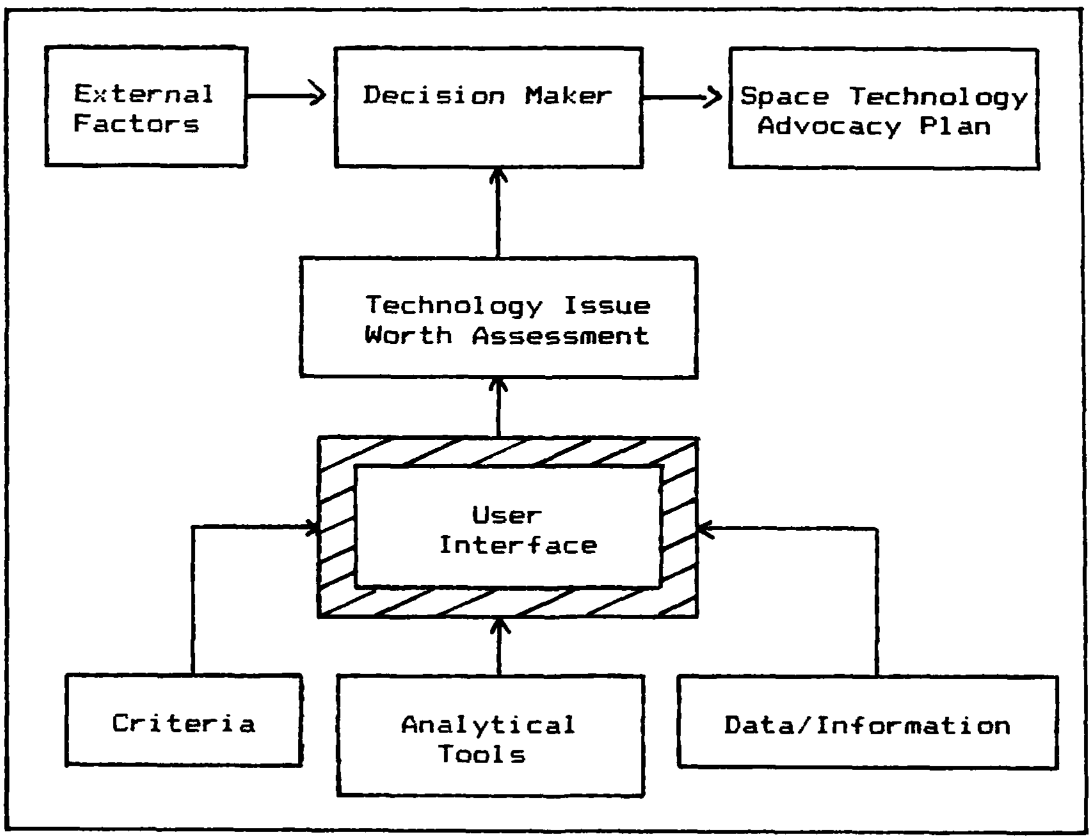

Figure 6-9. Space Technology Advocacy Model User Interface

The final element of the decision support methodology is the user interface. This section describes our perception of those requirements that are needed to transform our proposed decision support methodology into an actual computer-based decision support system. The actual user interface would most likely be a computer terminal whereby the decision maker or space technology expert can interface with both the database and the analytical tool with the appropriate algorithms. The intent in this section, therefore, is to define the general features that a computer-based decision aid must have if a truly effective user interface is to be achieved.

The computer-based decision aid for space technology advocacy should be microcomputer based. The microcomputer is an economical and effective means of processing the management information needed to arrive at informed decisions about space technologies. Lee [105:239-241] and Keen and Morton [136:4] list several reasons for choosing the microcomputer as the vehicle for decision support. We expand on these.

First, the microcomputer-based decision aid is "user-friendly" in the sense that the decision maker does not need professional programming skills. In other words, the decision maker can interact directly with the microcomputer to obtain decision support.

The second reason for basing this decision support aid on the microcomputer is the availability of improved soft-

ware. Highly interactive software packages exist that require very little training to operate effectively. For example, Expert Choice is an excellent sample of a user friendly and interactive software package. Appendix O is a copy of printout from Expert Choice.

A third reason for choosing microcomputers is the increasing managerial computer fluency. In other words, with the explosion in the availability of microcomputers, the new generation of space-technology experts and managers will bring with them an increased awareness of computers and management science. Also, with this increased fluency, these decision makers will be able and willing to use microcomputers to aid in decision making.

Fourth, the Air Force has and is currently providing microcomputers to many offices. For example, the Space Technology Center currently has several microcomputers that could run the algorithms described in this chapter.

Another important reason for using microcomputers is that microcomputers are constantly improving. In this respect, improvements in speed and storage capabilities will allow expansion of the database and will also allow the expansion of this advocacy model to provide additional capabilities (such as graphics capabilities).

The low cost and small size of microcomputers means that other space technology advocates could gain easy access to this model and the database. This decision support tool is designed with the Space Technology Center in mind. How-

ever, if similar staff functions within other major commands desire it, they, too, could use this space technology advocacy model in their planning functions. The database and the software model could be made readily available.

A final reason for using microcomputers is that it would be easy to add new management science models to the decision support system in order to evaluate alternative approaches to the space technology advocacy problem. In other words, as the decision support model expands, new features could be added. For example, a CPM or PERT model, or even GANTT chart software packages could be added, and easily integrated into the current decision support package. Also, sophisticated statistical subroutines could be incorporated into the decision support methodology that are specifically designed for analysis of group results [18; 64; 65; 77; 180]

To provide program control, database control, error protection and user assistance, we now list several common-sense features (partially derived from Keen and Morton [136]) that a computer-based decision support system must have if the user interface is to be effective and efficient:

1. Protection against premature program termination due to user input errors.

2. The program must be able to recover from input errors without starting over.

3. Ability to selectively display or modify user inputs.

4. Ability to provide help to the user at any time, especially when the user is unfamiliar with

the system.

5. Ability to selectively list the options available to the user whenever needed.

6. Ability to stop the program and restart it later without losing any data that has already been entered.

7. Ability to abort a routine without terminating the entire program.

8. Ability to control the overall flow of the program with as little effort as possible.

9. Ability to provide unique display algorithms as well (see [167; 268; 269; 270; 271; 272])

In summary, the microcomputer and user friendly software provide an excellent vehicle to interface the decision maker with this proposed decision support methodology.

Conclusions

> The outcomes obtained from various models used must now be interpreted in the light of practical, real-world considerations. A solution to a problem that has been simplified and possibly made amenable to calculation by idealization and aggregation is not necessarily a good solution to the original problem. Even if the model and its inputs are excellent, the conclusions proposed may still be unacceptable [189:59].

Up to this point we have only discussed some of the key elements in our space technology advocacy model (Figure 6-10). The four elements we have discussed (criteria, information requirements, analytical tools, user interface) provide the decision maker with a worth assessment of space technology issues. After the space technology assessments are made the decision maker must consider external factors before he presents his space technology plan. We define

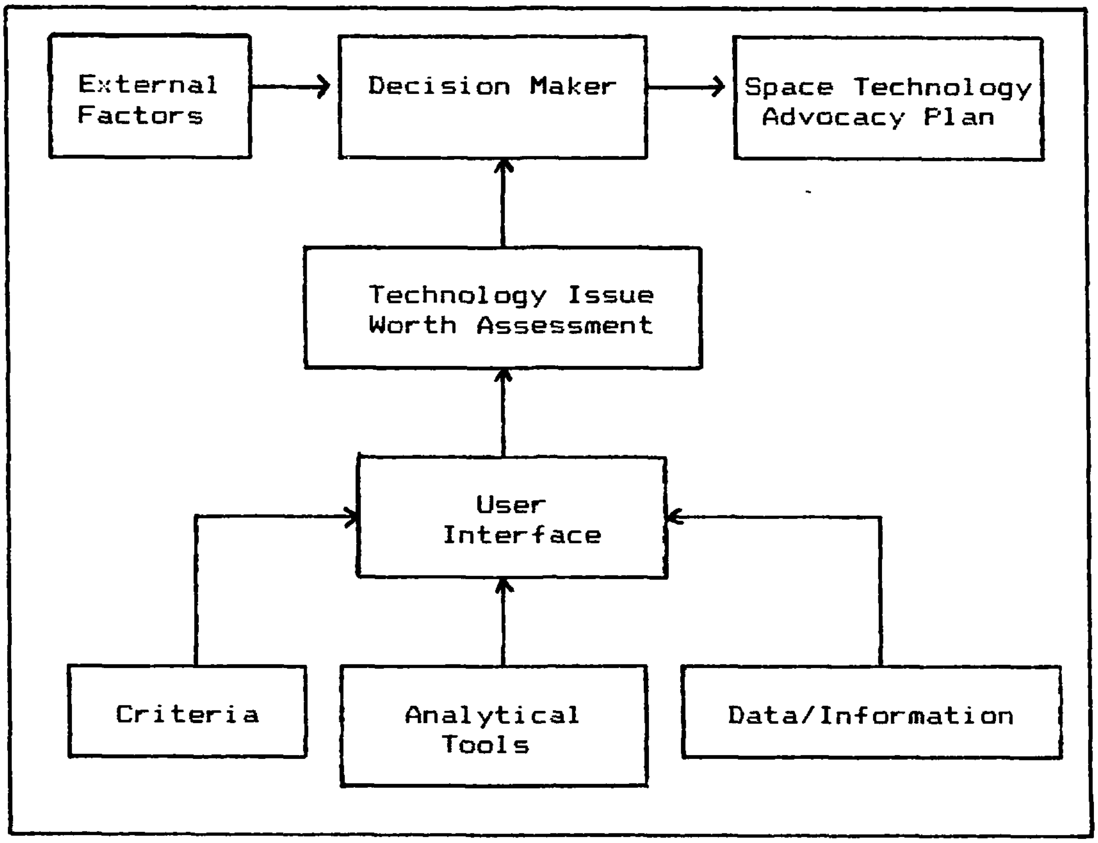

Figure 6-10. Space Technology Advocacy Model

external factors as those exogenous variables beyond the control of the decision maker. We discussed some of these factors in Chapter Four.

For example, to the extent that people agree about the importance of the technology issues, more resources (funding) should be advocated for those technology issues. To the extent that people disagree about the importance, their judgments tend to nullify each other and the technology issue tends to get a smaller share of the emphasis in the advocacy process. If a technology issue is important to the strategy of space technology, but there is disagreement

on implementation, i.e. the manner in which the technology issue should be advocated, then more information should be gathered so that the experts and the decision makers develop a better appreciation for the need to resolve the technology issue and can thus induce more cohesive action.

Other external factors that the decision maker must consider are policies, other advocates, the number of existing programs that already address a particular technology issue, laboratory resources and personnel, and national and organizational politics.

The next chapter presents the results of applying elements of our proposed decision support methodology to the worth assessment of space technology issues.

VII. Testing of the Space Technology Advocacy Decision Support Methodology

Introduction

The previous chapter discussed the three elements of a decision support system: information, analytical tools, and user interface. Also, the specific elements that would go into a decision support system for space technology advocacy were identified and discussed. However, the description of the elements of a decision support system is insufficient to determine the suitability and user acceptance of the system. In fact, it is necessary to address four general problems [24; 159:1] that determine whether or not a particular decision support methodology will be adopted. The first problem involves the degree to which the methodology fits the reality of the decision situation. The second involves the availability or lack of acceptable input data or information for use by the expert or decision maker in order to make informed judgments or decisions. The third problem involves the familiarity with or the lack of familiarity and knowledge of the techniques used in the decision support methodology. The final, and perhaps the most crucial problem involves the organizational stability necessary for the continued acceptance and use of a methodology.

We conducted an exercise to determine the suitability and acceptability of our proposed methodology. We were also interested to learn how well our methodology addressed the four problems listed above. We hoped to gain insight into

the impact and possible adoption of the methodology.

Eight people participated in the exercise. All of these participants are involved to some degree in the evaluation of space technology issues either at the laboratory level (AF Wright Aeronautical Laboratories with two participants) or at the technology planning level (AF Space Technology Center with six participants).

Demographic data is provided in Appendix K to show the broad cross section this group of eight people represent. Appendix L is a copy of the instructions provided to each of the participants in the exercise. Appendix M is the interview schedule (questionnaire) that each participant completed after they finished the exercise. Appendix N is the list of space technology issues that were evaluated by the participants. Appendix O is an example of the listing of the results of using the AHP in evaluating the space technology issues, including example histograms of the pairwise comparisons. The reader should refer to these appendices for the actual details of the exercise. The results of the participants' weighting of the space technology issues are not provided. Again, the purpose of the exercise was not to prioritize space technology issues but rather to gain some insight into the methodology itself. However, the responses to the questionnaire are provided and discussed below and are more appropriate for addressing the four problem areas discussed above.

Objectives of the Exercise

The objectives of the exercise were to investigate the validity, adequacy, suitability, and usefulness of our proposed methodology. All but two of the participants used the commercially available computer software Expert Choice (see Chapter 6) when evaluating the space technology issues. Another objective of the exercise was to determine the "user friendliness" of this type of software. Other objectives of the exercise were to obtain from the participants their responses in such areas as their understanding of what they were to do; their assessment of their own qualifications to evaluate space technology issues; their familiarity with analytical techniques; the suitability of the hierarchical model used in the exercise; the importance of consistency in making decisions; the availability of information for evaluating space technology issues with respect to the criteria; the "reasonableness" of the results of their evaluation; and finally, their inclination as to adopting the methodology for the evaluation of space technology issues.

Questionnaire Responses

The responses to the questionnaire as to the overall appropriateness of our proposed methodology are now presented. No statistical tests are employed in the following analysis. These would be inappropriate given our small sample size. However, the relevant data has been compiled and presented in the form of a frequency distribution.

Conclusions drawn from this data are based on a qualitative evaluation of the responses combined with our observations and experiences in conducting the exercise. Following each frequency distribution, a conclusion is made, followed by a short discussion.

Understanding.

Objective: The objective of the following question was to determine whether or not the participants understood the purpose of the exercise and the part they were to play in it. In effect, this question addressed whether or not the participants understood what they were supposed to do.

Q: I understood what I was required to do for this exercise in assessing the space technology issues.

not at all clear	
not very clear	X X
somewhat clear	
fairly clear	X
very clear	X X X X X

Conclusion: Most of the participants had a clear understanding of what was involved in this exercise.

Discussion: The two participants that responded that they did not have a clear understanding were the two participants that had never actually prioritized technology issues previously. Hence, they showed some hesitancy in actually evaluating space technology issues, especially those that were outside their field of expertise. Also, we observed a definite learning curve phenomenon in all of the partici-

pants. Some learned how to use the software more rapidly than others. However, the rapidity at which a participant "learned" the methodology did not appear to affect his response to this question. Overall, we feel that all of the participants understood what was expected of them. None of the participants showed any reluctance for expressing his preferences in the pairwise comparison of technology issues.

<u>Qualification</u>.

Objective: The objective of the following four questions was to elicit the participants' feelings as to their qualifications to evaluate space technology issues in and out of their area(s) of expertise.

Q: I feel qualified to assess technology issues outside my area(s) of expertise.

strongly disagree	
disagree	X X X X
not sure	X
agree	X X X
strongly agree	

Q: I feel qualified to assess technology issues outside my area of expertise in terms of the three criteria.

strongly disagree	
disagree	X X X
not sure	X X X
agree	X X
strongly agree	

Q: I feel qualified to use these three criteria in assessing space technology issues.

strongly disagree	
disagree	
not sure	
agree	X X X X X X X
strongly agree	X

Q: I feel qualified to assess technology issues in terms of military doctrine.

strongly disagree	
disagree	X
not sure	X
agree	X X X X X
strongly agree	X

Conclusion: The respondents in general felt qualified to evaluate space technology issues in terms of the criteria. However, only those who described themselves as "multidisciplinary" felt comfortable evaluating space technology issues across disciplines.

Discussion: The more experienced participants responded more favorably across the board to all four questions. Some of the less favorable responses could be explained in terms of some misunderstanding as to the actual definition and explanation of each of the criteria.

Analytic Techniques.

Objective: The objective of the following four questions was to obtain from the participants in the exercise an indication of their familiarity with the analytic hierarchy process, other analytical techniques, and their use of these

techniques in setting priorities in any aspect of their professional lives.

Q: Were you familiar with the Analytic Hierarchy Process prior to this? Indicate the level of familiarity on the following scale.

Not at all	1	X X
	2	X X
	3	X
Somewhat	4	X X
	5	
	6	
Very Much	7	X

Q: Have you ever used the Analytic Hierarchy Process as an aid for selecting or assessing possible alternatives (in any aspect of your job or profession)?

Not at all	1	X X X X X
	2	X X
	3	
Somewhat	4	
	5	
	6	
Very Much	7	X

Q: Do you currently use any formalized method or technique for assessing or prioritizing technology issues?

Yes	X X X
No	X X X X X

Q: I am now using or have used quantitative analytical methods in my work for setting priorities.

much too little	X X X
too little	X X X
about right	X X
too much	
much too much	

Conclusion: Most participants were unfamiliar with the AHP but knew of methods using pairwise comparisons. Also, most of the participants do not use, or use only rarely, any formal analytical techniques for setting priorities or for evaluating space technology issues.

Discussion: Only one of the participants used a method of pairwise comparisons regularly, although it was unclear if the AHP was the methodology he used. Other than this single person all of the other participants wanted to use analytical techniques but were unsure of which ones were suitable and also how to "implement" them in their work.

Consistency.

Objective: The objective of the following two questions was to elicit from the participants an indication of whether or not consistency in their decisions was important to them and whether or not the measure of their consistency in evaluating space technology issues was a valuable aid to them when they used the AHP to evaluate these space technology issues.

Q: The measure of my consistency in setting space technology issue priorities is an important element in using this approach.

strongly disagree	
disagree	X
not sure	X X
agree	X X X X
strongly agree	X

Q: Consistency is important to me when making decisions.

strongly disagree	
disagree	
not sure	X X X
agree	X X X
strongly agree	X X

Conclusion: In general the participants thought consistency was important, but not overly so.

Discussion: All of the participants used the measure of their consistency as calculated using the AHP to determine if their pairwise comparisons were relatively consistent. However, some of the participants did not really understand what consistency meant. Others who did understand did not seem overly concerned with making their choices more consistent. The best use of the consistency index was to identify possible misentries. Overall, practically all of the participants were very consistent (less than Ø.1Ø inconsistency index) at evaluating the technology issues with respect to the criteria. If a participant was inconsistent it was in the pairwise comparison of planning horizons with respect to the goal and in the pairwise comparison of the criteria with respect to the planning horizon. Many of the participants were indecisive in setting these priorities.

<u>Model</u>.

Objective: The objective of the following question was to obtain from the participants in the exercise an indication of the validity of the hierarchical model employed in the evaluation of the space technology issues.

Q: The hierarchy is appropriate for this type of analysis.

strongly disagree	
disagree	X
not sure	X
agree	X X X X X
strongly agree	X

Conclusion: As a simple, standardized model with which to evaluate the methodology the model was good.

Discussion: All of the participants questioned, to one degree or another, the model used to evaluate the technology issues. However, all participants were able to make the comparisons and trade-offs necessary to evaluate the technology issues. On the other hand, we strongly urge, and the participants agreed with us, that the actual hierarchical model should be created by the decision maker to reflect his goals, objectives, criteria, and decision situation. Overall, the participants thought the model was adequate for the intended purpose.

Goal.

Objective: The objective of the following four questions was to obtain from the participants in the exercise an indication as to the ultimate goal for resolving space technology issues.

Q: The ultimate goal for resolving space technology issues is to provide a broad technology base to meet current and future operational needs.

strongly disagree	
disagree	
not sure	X X
agree	X X X X X
strongly agree	X

Q: The ultimate goal for resolving space technology issues is to provide a broad technology base that is responsive to operational needs.

strongly disagree	X
disagree	X
not sure	X
agree	X X X X X
strongly agree	

Q: The ultimate goal for resolving space technology issues is to provide a broad technology base that is responsive to operational needs currently known, projected, or as yet unidentified.

strongly disagree	X
disagree	
not sure	X
agree	X X
strongly agree	X X X X

Q: The ultimate goal for resolving space technology issues is to build space systems.

strongly disagree	X
disagree	X X X X X
not sure	
agree	X X
strongly agree	

Conclusion: The participants expressed many opinions as to

the ultimate goal for resolving space technology issues.

Discussion: Many opinions were expressed and good arguments presented to support those opinions. A comprehensive statement of the goal would be multidimensional in nature and be a multiperspective definition.

Criteria.

Objective: The objective of the following four questions was to obtain from the participants in the exercise an indication of their understanding of the criteria, the appropriateness of using these criteria in evaluating space technology issues, and whether or not the participants could actually evaluate the space technology issues with respect to each of the criteria.

Q: The three criteria represent a good way to evaluate the potential military strategic and technical utility of space technology issues.

strongly disagree	
disagree	
not sure	X
agree	X X X X X X X
strongly agree	

Q: Technology issues need to be assessed and prioritized in the context of the three criteria.

strongly disagree	X
disagree	
not sure	X X X X
agree	X X X
strongly agree	

Q: Of the three criteria, which one was easiest to apply?

Criteria 1	X X X X X X
Criteria 2	X X
Criteria 3	

Q: Of the three criteria, which one was most difficult to apply?

Criteria 1	X
Criteria 2	X X
Criteria 3	X X X X X

Conclusion: The criteria are "good" ones to use in the evaluation of space technology issues.

Discussion: All of the participants expressed some concern over the "fuzziness" of the criteria. However, we observed that none of the participants were unable to make the pair-wise comparisons required with respect to each of the criteria. We also noted that much discussion was generated concerning what was meant by each of the criteria. We think this could be a valuable organizational aid in better defining goals and objec ves that are ill-defined. Most participants thought criterion 1 was the easiest to apply because they were most familiar with meeting mission requirements. On the other hand, some of the participants were uncomfortable with the third criterion because they did not know how to measure a "hedge" against technological surprise or uncertainty. There was some correlation with age/experience and the level of comfort with using Criterion 3. Those older and more experienced had less difficulty

applying Criterion 3.

<u>Criterion 1</u>.

Objective: The objective of the following two questions was to obtain from the participants in the exercise an indication of their understanding of the first criterion and their ability to apply it in the pairwise comparison of space technology issues.

Q: The description of Criterion 1 made sense to me.

strongly disagree	
disagree	
not sure	
agree	X X X X X X
strongly agree	X X

Q: I was able to apply Criterion 1 in the pairwise comparison of space technology issues.

strongly disagree	
disagree	X
not sure	
agree	X X X X X X X
strongly agree	

Conclusion: Criterion 1 was suitably defined and applied.

Discussion: Most participants readily understood this criterion and only one person had problems applying it. However, we must point out that this person was also the least experienced of all the participants (second lieutenant).

<u>Criterion 2</u>.

Objective: The objective of the following two questions was to obtain from the participants in the exercise an indica-

tion of their understanding of the second criterion and their ability to apply it in the pairwise comparison of space technology issues.

Q: The description of Criterion 2 made sense to me.

strongly disagree	
disagree	
not sure	
agree	X X X X X
strongly agree	X X X

Q: I was able to apply Criterion 2 in the pairwise comparison of space technology issues.

strongly disagree	
disagree	
not sure	
agree	X X X X X X X
strongly agree	X

Conclusion: This criterion was suitably defined and applied.

Discussion: The participants understood this criterion and could apply it to the various technology issues. However, two of the participants felt that they would have to do further research on several of the technology issues before they would be willing to make an "honest" evaluation. In the same vein, both of these participants did indicate that the information for this type of evaluation was available in the MSSTP and in other technical reports.

<u>Criterion 3</u>.

Objective: The objective of the following two questions was to obtain from the participants in the exercise an indica-

tion of their understanding of the third criterion and their ability to apply it in the pairwise comparison of space technology issues.

Q: The description of Criterion 3 made sense to me.

strongly disagree	
disagree	
not sure	X X
agree	X X X X
strongly agree	X X

Q: I was able to apply Criterion 3 in the pairwise comparison of space technology issues.

strongly disagree	
disagree	
not sure	X X X
agree	X X X X
strongly agree	X

Conclusion: Criterion 3 is the "fuzziest" criterion and the most difficult to apply, but not overly so.

Discussion: All participants had questions for us about this criterion. However, again none of the participants showed any reluctance to make the pairwise comparisons using Criterion 3. All of the participants agreed that it would be difficult if not impossible to quantitatively describe this criterion. The method of pairwise comparisons used in the AHP as well as the verbal scale seemed to allow each of the participants to make the evaluations.

<u>Information</u>.

Objective: The objective of the following four questions was to obtain from the participants in the exercise an

indication of the existence and the availability of information that could be used by the expert or decision maker in evaluating the various space technology issues in a pairwise fashion.

Q: The information required for this type of analysis does not currently exist.

strongly disagree	X
disagree	X X X X X X
not sure	
agree	X
strongly agree	

Q: The information available to me about the space technology issues is adequate for this type of assessment in the context of criterion 1.

strongly disagree	
disagree	X X
not sure	X
agree	X X X
strongly agree	X X

Q: The information available to me about the space technology issues is adequate for this type of assessment in the context of criterion 2.

strongly disagree	
disagree	X X
not sure	X
agree	X X X
strongly agree	X X

Q: The information available to me about the space technology issues is adequate for this type of assessment in the context of criterion 3.

strongly disagree	
disagree	X X
not sure	X X X
agree	X X
strongly agree	X

Conclusion: The information necessary to evaluate space technology issues with respect to the three criteria exists.

Discussion: Those who were most experienced and familiar with space technology issues agreed that the information exists. Those less familiar did not know whether or not the information exists. We originally hypothesized that all would agree that the information exists. The MSSTP would be a good place to start.

<u>Results</u>.

Objective: The objective of the following four questions was to obtain from the participants in the exercise an indication of the validity of the results of their pairwise evaluation of space technology issues. In other words, were the results reasonable and did the results reflect the actual preferences of the participant.

Q: The results of the assessment are close to how I would rank order the space technology issues in order of importance.

strongly disagree	
disagree	
not sure	X
agree	X X X X X
strongly agree	X X

Q: I feel that decisions made by using this system would more closely reflect the attitudes and beliefs of the decision maker than if I did not use the system and arbitrarily developed a scoring model.

strongly disagree	X
disagree	
not sure	X
agree	X X X X X X
strongly agree	

Q: The results using this approach are the same that I would obtain if I did not use this approach.

strongly disagree	
disagree	X
not sure	X X
agree	X X X X
strongly agree	X

Q: The results using this approach would be valuable in setting priorities for budgetary decisions for space R&D technology programs.

strongly disagree	
disagree	
not sure	X X
agree	X X X X X
strongly agree	X

Conclusion: In general the proposed methodology and

criteria captured the space technology issue preferences of the participants. The AHP is an adequate tool for eliciting the preferences (expert opinion) of decision makers and space technology experts.

Discussion: All of the participants who had previously prioritized space technology issues agreed with the final ranking of the issues as calculated from their pairwise comparisons and the hierarchical model. However, all participants were unsure of the relative weights assigned to the various levels within the hierarchy. It would be interesting to determine the stability of individual preferences over time. This could be done by having the expert make the technology issue evaluations several times over an appropriate timespan.

Adoption.

Objective: The objective of the following five questions was to obtain from the participants in the exercise an indication of their willingness to adopt the the AHP as a part of the organizational routine for prioritizing space technology issues.

Q: I would consider using this approach in the future in a formalized manner to assess technology issues.

strongly disagree	
disagree	
not sure	X
agree	X X X X X X
strongly agree	X

Q: The overall quality of my decisions would be increased by using this methodology because of the formalized structure of the problem and the criteria used.

strongly disagree	
disagree	X
not sure	
agree	X X X X X X
strongly agree	X

Q: This method requires too much time and effort to compare and prioritize space technology issues.

strongly disagree	X X X
disagree	X X X X
not sure	X
agree	
strongly agree	

Q: The manner in which technology issues are currently assessed is adequate and should not be changed.

strongly disagree	X X X
disagree	X X X X X
not sure	
agree	
strongly agree	

Q: After participating in this exercise I would adopt this methodology and the criteria whenever I must make an assessment of a set of space technology issues.

strongly disagree	
disagree	X
not sure	X X X
agree	X X X
strongly agree	X

Conclusion: Most participants would accept and use the proposed methodology.

Discussion: All of the participants found the methodology

to be straightforward and easy to apply. However, some were concerned with our hierarchical model and the criteria we used. We agreed that the actual hierarchical model, the goals, objectives, and criteria to be used should be elicited from the decision maker and should reflect his decision situation. Again, the most exciting result from the exercise was that the simple model used was adequate for capturing the preferences of the participants. Complex models may not perform better. This would be an interesting area for further investigation.

Summary and Overall Conclusions

We must stress that the results of our exercise are not statistically significant. However, the responses from the eight participants are *highly* encouraging as to the suitability, adequacy, usefulness, and validity of our proposed methodology. We feel that we can make the following generalizations concerning the proposed methodology.

First, the hierarchical model and the method of pairwise comparisons (the AHP) are good tools for eliciting the subjective preferences of the experts. Corollary to this is that the methodology does adequately capture the true preferences of these same experts.

Second, the interactive nature of the software used (Expert Choice) and the presentation of results in a "nice" way are invaluable in gaining the interest and even enthusiasm of potential users.

Third, the information necessary to evaluate space technology issues on the basis of doctrine and strategic utility does currently exist.

Fourth, we found that the methodology provides an excellent tool for intra- and inter-organizational dialogue as to the clarification of goals and objectives and reduction of uncertainty. In other words, the use of and the results from the methodology stimulated communication among the experts. This in itself can increase the knowledge and information available to the experts and provide a vehicle for better informed judgments.

Fifth, we found that the assessment of technology issues did not have to depend on concept linkage. The participants were able to evaluate and compare technology issues according to the three criteria presented.

Sixth, although not directly investigated, the presentation of histograms of the pairwise comparisons and the group results would be valuable aids in group problem solving sessions. All of the participants agreed that such information would help them make better informed evaluations of space technology issues.

Finally, we found that the most difficult part of "selling" this methodology would be in educating the potential users as to the good features and possible drawbacks of the methodology. However, we did find that the participants learned fairly rapidly and were able to proceed without our assistance after approximately 30 minutes.

In summary we found our proposed decision support methodology addressed the four problem areas introduced at the beginning of this chaper. The methodology used to elicit subjective judgments seems to fit the reality of the decision situation. The AHP technique for eliciting preferences was easily learned and applied by all the participants. Information needed to make informed judgments is available in the MSSTP and elsewhere. Along with this, the methodology can serve to identify additional information requirements. If available this new information could be added to or referenced in the MSSTP database. Our decision support structure does not directly address the fourth problem that can impact organizational acceptance and use of a methodology. We did not analyze nor speculate as to the organizational stability of the AFSTC. However, we believe the decision support structure that we propose has the flexibility to be applied in a variety of organizational settings.

The next chapter presents our final results and conclusions. In it we identify areas for further research. However, the methodology presented in the previous chapters plus the results presented in this chapter are highly encouraging and could lead to direct implementation of a decision support system for use by the Space Technology Advocate.

VIII. Recommendations and Conclusions

> Do not hamper any research, support heavily research that has a predictable payoff; and reduce uncertainty concerning the military and strategic usability of other technology areas and issues [187:62].

Conclusions

We began this research effort thinking that we would develop algorithms to improve and expand the capabilities of a computer-based space technology resource allocation (portfolio selection) model called TRUMP. TRUMP used the information and database of the MSSTP. Accordingly, we began an indepth analysis of the MSSTP and TRUMP and at the same time researched the available management science literature on R&D portfolio selection models.

From our review of the literature we discovered that hundreds of R&D decision models exist but few are currently being used. We found that these decision models inadequately address the inherent risk and uncertainty of R&D decision situations. In addition, most of these decision models failed to include the decision maker as an integral factor in the modeling process. This, too, was a factor in the low acceptance rate of many of the decision models we researched. For example, TRUMP was abandoned because decision maker preferences were not considered in the methodology. This naturally led us to seek an alternative approach to the space technology advocacy problem. The approach we took was to develop, in lieu of a decision model, a decision support

methodology that would assist the decision maker in the decision making process. This entailed a comprehensive analysis of the space technology advocates' decision situation. We studied the R&D environment and developed a hierarchical approach to modeling this environment. From this we developed criteria that could be used to assess the strategic and technical utility of space technology issues. Using these criteria the decision maker can focus on the strategic appreciation of the technology issues and their relative worth to military space strategy and doctrine and military space technology.

Finally, we described the information requirements and the analytical tool (the AHP) which could be used by the decision maker, with the appropriate user interface, to apply the criteria in a worth assessment of space technology issues. This worth assessment, in conjunction with an appreciation for the external factors in the decision situation, allows the decision maker to develop a space technology advocacy plan that is based on doctrine and on an appreciation for the strategic nature of the problem. This decision process is modeled in Figure 8-1.

Finally, we conducted an exercise to test the validity, suitability, and acceptability of our proposed decision support methodology. Eight space technology experts applied the criteria to sets of space technology issues within the context of the analytic hierarchy process. Their response to our proposed modeling of the space technology advocacy

problem leads us to conclude that we have established a firm foundation for development of our proposed methodology into a microcomputer-based decision support system. In addition we reached some specific conclusions.

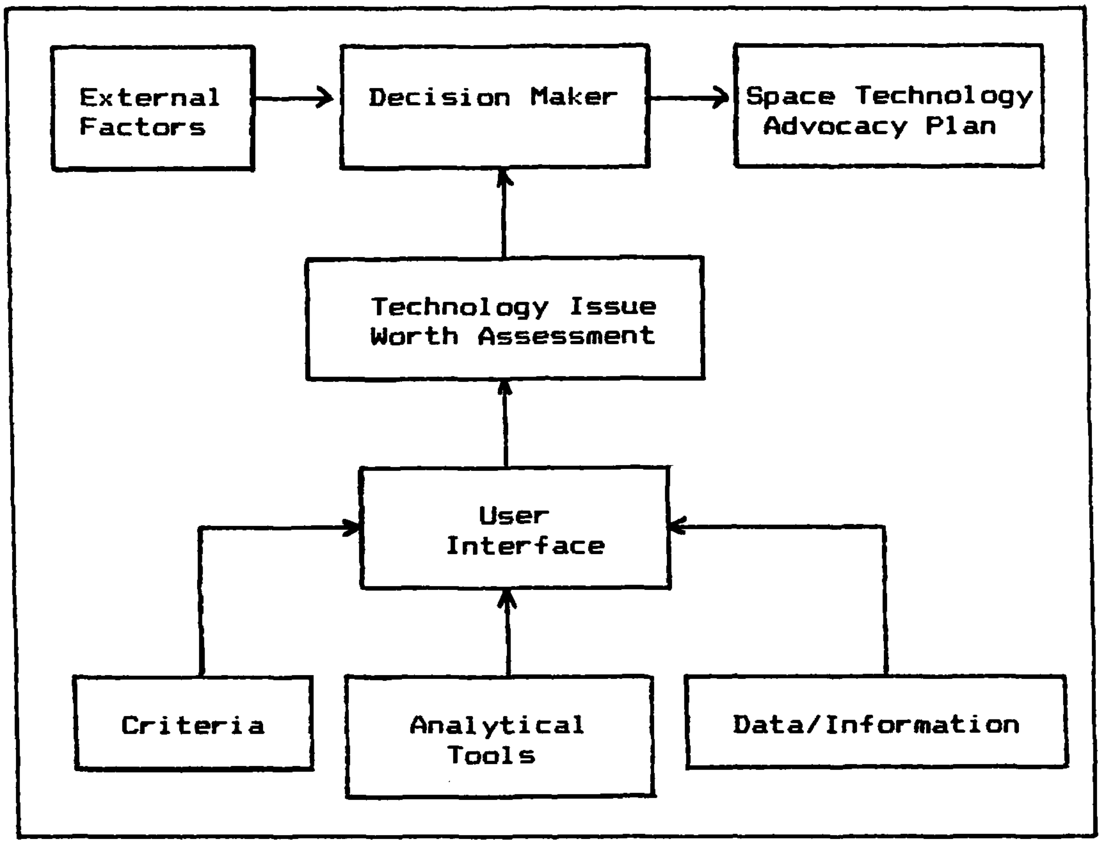

Figure 8-1. Space Technology Advocacy Model

1. Although it was impossible to determine if better decisions result from our model, we did discover that the participants in our exercise felt that the quality of their decisions would improve if they structured the problem as we have and applied the criteria using the AHP.

2. Interactive programming techniques increase the value of decision support systems. However, if our proposed

methodology is transformed into a computer-based decision support system, then it is essential that the decision maker participate in the actual design of the system. In addition, the system must be adaptive and developed in a participatory manner.

3. The use of the computer to elicit the subjective judgments and preferences of space technology experts guarantees that the questions and results are consistently developed. This standardization is important when performing sensitivity analysis.

4. The AHP adequately captures the subjective judgments and preferences of the space technology experts. Moreover, the AHP, in the context of a worth assessment of space technology issues, creates a great deal of information in the form of pairwise comparisons. This information can be automatically displayed to the decision maker or a group of experts as an aid to effective dialogue within the organization. Helin and Souder [110:159] say it best:

> All evidence points to the fact that where they are successful, it is because the models and formulae have somehow improved the organizational decision making behavior. That is, it is not the analytical or decision optimizing properties of the models that are of value. Rather, the benefits follow from the fact that the "process" of using the model forces a conceptual examination of alternatives and decision premises, thereby creating important dialogues which may not otherwise take place in an organization [110:159].

Recommendations

The contribution we have made in describing a decision

support model for the space technology advocate is only a first step towards understanding and deriving useful information for R&D planning. Using the conceptual framework we have developed, we feel follow-on analyses can be accomplished to better scope and define the nature of space-related military R&D processes. Analyses could build on the techniques we have introduced to better manage the subjectivity and complexity inherent in R&D processes. Furthermore, given consensus on subjectively derived data, many of the quantitative methodologies that address R&D portfolio selection problems in the literature may have real utility in application to space R&D portfolio selection decisions.

Following are some general areas worthy of further research. Studies in these areas would be logical extensions of the work we have begun in conceptually modeling military space R&D processes.

1. Develop an interactive group decision making analysis tool centered on the AHP with built-in computer utilities for computing basic statistics and displaying histograms of group results. Explore its utility as a means to evaluate space technology issues in a group environment. Some specific areas worthy of research include its use as a mechanism to arrive at group consensus, and as a means to identify areas requiring additional information or research (highlighted by wide divergence in individual results). Our research indicated this approach would be most beneficial in a group setting.

2. Apply the AHP in the context of mission area analyses. We introduced a hierarchy for considering technology issues from a mission needs perspective in Chapter Three and expanded on it in Appendix G. The AHP could be used to elicit worth assessments of the various missions and tasks that comprise this hierarchy. Additionally, technology issues could be further specified using the AHP and criteria elicited from the decision maker. Technology issues could then be prioritized on the basis of their linkage to missions and mission tasks.

3. Focus on the subjective elements used as data inputs for TRUMP. Use the AHP to elicit probabilities of success, and estimates for technology program schedules and costs. We believe the AHP would be particularly useful in deriving and evaluating criteria for these elements and help reduce the area of uncertainty surrounding these estimates. Perhaps estimates solicited using the AHP would be meaningful inputs for quantitative risk analyses.

4. Explore "what if" analyses using other analytical techniques in conjunction with the AHP (to elicit subjective estimates). These analyses could include development of funding scenarios, resource constrained advocacy programs, and simulation studies to explore the impacts of alternative R&D approaches and decisions.

5. Develop the conceptual decision support model we presented into a comprehensive, micro-computer based decision support system. Such a package should include

automated interfaces between the analytical tool (the AHP) and the database (the MSSTP), as well as the algorithms necessary to present the database information the decision maker needs to make his assessments. It could also include an interface to external factors such as budget information, other advocates for given technology issues, and other data useful to the space technology advocate in preparing and presenting his advocacy plan.

Appendix A: Selected Military Tasks from MSSTP

Table A-1

Tasks Selected in Response to Strategic Threat

To provide/Ensure Capabilities for	Military Task Selected (Task Number)
Tactical Warning of strategic attack	Warning of ballistic missile attack on CONUS (1) Warning of air vehicle attack on CONUS (2) Warning of space-based weapon attack on CONUS (3)
Defense of CONUS	Defense of CONUS from attack by ballistic missiles (4) Defense of CONUS from attack by air vehicles (5)
Improvements of strategic land and sea-based offensive force capabilities	Ballistic missile accuracy enhancement (6) Dynamic strategic force construction (7) Strategic aircraft force reconstitution (8) Strategic aircraft penetration enhancement (9) Communications for strategic management (10) Countermeasures against early warning radars (11) Countermeasures against space communications systems (12)
Improved strategic weapon delivery	Space weapon delivery (13) Discriminating attack capability (14)

TABLE A-2

Tasks Selected in Response to Tactical Threat

To Provide/Ensure Capabilities for	Military Task Selected (Task Number)
Capability improvement by NATO	Warning of air vehicle attack on theater forces (15) Defense of tactical forces from attack by air vehicles (16) Warning of tactical ballistic missile attack on theater forces (17) Tactical target identification and site location (18) Defense of tactical forces from attack by tactical ballistic missiles (19) Improved intratheater communications (20)
Warning/defense of naval task force	Warning of air vehicle attack on naval task force (21) Defense of naval task force from attack by air vehicles (22)

TABLE A-3

Tasks Selected in Response to ASAT and Space Threat

To Provide/Ensure Capabilities for	Military Task Selected (Task Number)
Enhancement of satellite survival and control of space operations	Warning of air vehicle attack on U.S. space systems (23) Defense of U.S. space systems (24) Hostile space systems destruction (25)
Survival through reconstitution	Launch of U.S. space systems (26)

Appendix B: Mission Area/Task Linkages

Table B-1. DoD Mission Area/Task Linkages

DoD Major Mission Area	Covered by Selected Military Task No. (from Appendix A)
100 Strategic Warfare	
110 Strategic Offense	6,13,14
120 Strategic Defense	1,2,3,4,5,23,24,25
140 Strategic Support	26
200 Tactical Warfare	
210 Land Warfare	6,13,14
220 Air Warfare	16
230 Naval Warfare	21,22
240 Theater Nuclear Warfare	13,16,19
250 Space Warfare	23,24,25
260 Strategic Mobility	N/A
270 Chemical Warfare	6,13
300 Intelligence and Command, Control, Communications	
310 Centrally Managed Intelligence	N/A
320 Tactical Intelligence & Related Activities	15,17,18
330 Strategic C-cubed Programs	7,8,9,10
340 Theater & Tactical Command, Control	20
350 Warfare Command and Control	No task
360 Defensewide C-cubed Program Support	No task
370 EW and C-cubed Countermeasures Systems	11,12

Table B-1. DoD Mission Area/Task Linkages (continued)

DoD Major Mission Area	Covered by Selected Military Task No. (from Appendix A)
400 Defensewide Mission Support	
410 Space Launch and Orbital Support	26
420 Global Military Environmental Support	No task
430 Nonsystem Training Devices	N/A
440 Technical Integration	N/A
450 Test and Evaluation Support	N/A
500 Science and Technology Programs	
500	N/A

Appendix C: Military Functions and Functional Areas

TABLE C-1

Military Functions and Functional Areas

Functional Area	Functions
Surveillance	Air Vehicle Detection and Track Ballistic Missile Detection and Track Nuclear Detonation Detection and and Location Space Vehicle Detection and Track Surface Target Surveillance and Reconnaissance
Communications	Communications
Navigation	Navigation
Environmental Monitoring	Environmental Monitoring
Force Application	Air Vehicle Destruction Ballistic Missile Destruction Space Vehicle Destruction Surface Target Destruction Electronic Warfare
Space Operations	Space Activities Space Launch

Appendix D: Concept/Task Linkages

The figure shown below depicts the military tasks (derived in Volume I of the MSSTP) necessary to support each of the concepts described in Volume II. The 34 concepts shown are based on the results of the first iteration of the MSSTP and this list is no longer valid. It is shown here for demonstration purposes only.

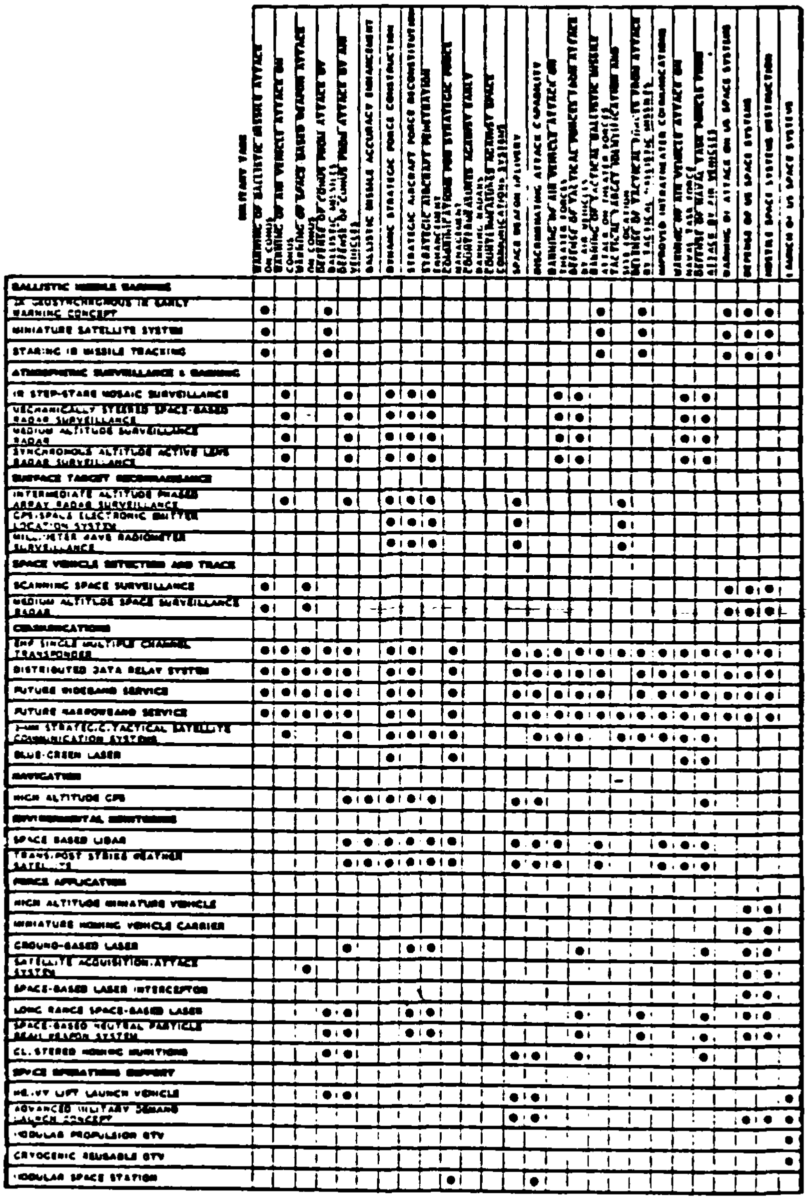

Figure D-1. Concept/Task Linkage in the MSSTP

Appendix E: Technology Issues and Technology Disciplines

TABLE E-1

Technology Issues and Technology Disciplines

Propulsion

- Primary
- Secondary
- Satellite

Navigation, Guidance and Control

- Attitude
- Orbit
- Pointing accuracy and stability

Power/Energy

- Solar
- Batteries
- Fuel Cells
- Nuclear
- Power Distribution

Information Processing

- Signal Processor
- Computers/Software
- Circuitry
- Hardening

Materials

Cryogenics/Thermal Control

- Refrigerators
- Thermostats
- Heat Pipes

Structures

T/M and Communication

- Antennas
- Amplifiers and Oscillators
- RF Characteristics

Weapons

- Kinetic Energy
- Directed Energy

Sensors

- Radar
- Infrared
- Optical
- Measurement

Man in the System

- Life Support
- Man/Machine Interface

Manufacturing

Natural Environment

- Spacecraft Charging
- Weather
- Van Allen Belt

Survivability

Appendix F: High Payoff Technologies

Table F-1. High Payoff Space Technologies

TECHNOLOGY	SYSTEM PAYOFF
Propulsion	
Low-Thrust Chemical	Increased Payload
Heavy Lift Chemical	Military Access to Space
Advanced Propulsion Systems	Large Structures, OTV
Electric Propulsion	Maneuver Capability
Power	
Long-Life Batteries	Improved Specific Power
Advanced Power Processing	Improved Survivability
High Voltage Distribution	Increased System Capability
Nuclear Reactors	Reduced Weight
	Enable Advanced Concepts
Materials	
Advanced Composites	Increased stiffness
Improved Material Capability	Reduced Weights
	Survivability
Structures	
Large Deployable Antennas	Space Radars
Space Based Fabrication, Assembly, Deployment	Space Weapons
Lightweight Optics	Military Access to Space
Hot Structures	
Information Processing	
Spacecraft Processors	
- Very High Speed	
- Low Power Requirements	
On-Board Data Processing	Flexible/Survivable Systems
Advanced Signal Processors	
- Bandwidth	Autonomous Spacecraft
- A/J Margin	Multimission, High Data Capacity
Signature Model Prediction Accuracy	On-Board Processing
Image Processing System Improvements	
Hardened Components	

Table F-1. High Payoff Space Technologies (cont.)

TECHNOLOGY	SYSTEM PAYOFF
<u>Cryogenics/Thermal Control</u>	
Active Cryogenic Refrigerators	
– Lifetime	
– Thermal Load	
Passive Cryogenic Coolers	Increased Orbital Life
– Lifetime	LWIR Capability
Deployable Radiators	
– Specific Mass	
<u>Weapons</u>	
Laser Specific Energy	
Laser Power	Space Defense
Laser Reactant Space Storage Capability	Advanced Submarine Communications
Laser Beam Quality	Weapon Feasibility
Pointing and Tracking	
<u>Telemetry and Communications</u>	
Data Rates to Small, Mobile Terminals	
K-Band Technology for Telecommunications	High Accuracy Wideband Links
60 GHz Technology for Telecommunications	Anti-Jam, LPI Service
High Data Rate Crosslinks	Nulling
– Microwave Technology	Multi-User Capability
– Laser Communications	Survivable Mission Data
High Performance Multi-Beam Antennas	
High Power, High Efficiency Traveling Wave Tube Amplifiers	
<u>Sensors</u>	
Large Diameter Mirrors	
Focal Plan Detectors	
– Number of Detectors	High Resolution, Scan Rate/Light Weight
– CCD Technology	
– Low Temperature Ops	Spatial/Temporal Data
Contamination Control for Systems	Detection/Track Information
Low Noise Power Amplifiers for Radar Applications	Small Target Detection
<u>Navigation, Guidance, and Control</u>	
Pointing Control Systems	Maneuvering Capability
– Accuracy	Targeting Capability
– Stability	Increased Life
Gyroscope Life	

Appendix G: Mission Needs Hierarchy

Introduction

In Chapter Five we described a hierarchical model that showed the connectivity between technology issues and national interests. We identified two separate paths for evaluating the importance of technology issue support to national interests. One path led from technology issues directly to the scientific-technological instrument of national power, and then through policies and objectives to national interests. The second path was through a mission needs hierarchy that connected to the military instrument of national power and then through policies and objectives to national interests. We briefly summarized the elements of this hierarchy in Chapter Five.

In this appendix we expand our discussion of the mission needs hierarchy. We explain why we think it represents an improvement over the hierarchical structure represented in TRUMP and how it could be useful to the space technology advocate in evaluating space-related technology issues. We then discuss the hierarchy in detail, defining the various levels and the elements that constitute each level.

Background

Recall in Chapter Three we described how military tasks that could be performed in space were derived in the MSSTP. Air Force doctrine, as described in AFM 1-1 [6] and AFM 1-6

[8], defined Air Force missions. They included Space Operations as one of nine primary Air Force missions. Under Space Operations were three categories: space support, force enhancement, and space defense. The MSSTP used this baseline in generating military tasks that could be performed in space. Twenty six tasks were identified (shown in Appendix A). Tasks were then linked to task requirements (functions), which were linked to system concepts. Technology issues which needed to be resolved to support concepts were linked to concepts to complete the hierarchy, as shown in Figure G-1.

```
[National Needs, National Security Objectives, Policies]
                          |
                [implicit in the MSSTP]
                          |
                          |
           DOD Mission Areas, Mission Arenas
                          |
             Tasks ("Missions" in TRUMP)
                          |
  Functions ("Mission Requirements" in TRUMP)
                          |
                          |<-----Performance Parameters
                      Concepts
                          |
                  Technology Issues
                          |
                 Technology Programs
```

Figure G-1. MSSTP & TRUMP Hierarchy

We took a slightly different approach in developing our hierarchy. As we described in Chapter Four, there are many facets to doctrine. We defined three categories of doctrine: fundamental, environmental, and organizational. We

showed how the MSSTP hierarchy is basically derived from organizational doctrine, which is what AFM 1-1 [6] and AFM 1-6 [8] primarily represent. We defined organizational doctrine to be "beliefs concerning how to conduct warfare, based on current thinking and constrained by existing policies." Environmental doctrine was defined as "beliefs about how the environment (the physical medium military forces operate in) can be exploited to support new tasks to accomplish military objectives." Environmental doctrine is not necessarily constrained by policy, but is closely linked with technology. Environmental doctrine both drives and is driven by technology.

We propose that building a mission needs hierarchy on the basis of environmental doctrine provides a better foundation from which to evaluate technology issues necessary to support a broad-based R&D plan for the future. It offers several advantages over more restricted hierarchies founded on organizational doctrine. For example, environmental doctrine is more "free-wheeling" and unconstrained by policies and current thinking. Thus, it is easy to incorporate potential military tasks that possibly could be accomplished in the operational environment. Such tasks may be prohibited by existing policies or laws. Additionally, it focuses attention on the environment in which military operations are conducted, promoting more forward thinking about how new technologies could be applied to accomplishing military tasks in the operational environment. Finally, this linkage

between environmental doctrine and technology is symbiotic; both mutually support one another and the focus is always to the future on new ways military operations can be supported by technology, or new capabilities that technology must provide to support environmental doctrine.

We believe this philosophical basis is especially applicable to military space R&D planning. The planning horizon for R&D extends well into the future. We have shown that forecasting techniques that attempt to predict outcomes over five years in the future are historically inaccurate and probably will not account for all possible or even likely futures. Thus, techniques that are limited by current thinking will yield futures that only make sense from a current perspective on the way things are. On the other hand, if we incorporate an environmental doctrine perspective in our approach to forecasting future technological requirements, we help overcome this emphasis on current thinking and broaden our scope. This allows us to consider a greater variety of possible futures and to be more free thinking in generating these outcomes.

Note that we have said nothing as to how technology issues should be weighted when considered from an environmental doctrine perspective. Realistically, we would expect any mission needs hierarchy to incorporate both organizational and environmental doctrinal thinking. Organizational doctrine addresses known military requirements and the R&D efforts necessary to provide these requirements. Environ-

mental doctrine attempts to speculate on potential applications and possible exploitations of technology to support military tasks. We would surmise that initially technology issues generated from an environmental doctrine perspective would be weighted rather low against technology issues related to existing military deficiencies. However, as a particular environmental doctrine gains acceptance, then the technology requirements to support it increase in stature. We believe it is important to identify these issues as soon as possible. Whether they are weighted high initially is not as important as ensuring they are documented as potential R&D benefits.

We are now ready to describe the mission needs hierarchy we have developed from an environmental doctrine perspective. However, we must note some limitations up front. First of all, since our original objective was to provide a hierarchical structure the Air Force Space Technology Center could use in their advocacy program, we had to consider military space R&D requirements from an Air Force perspective. In this regard, we broadly interpreted policy statements that include space as part of the Air Force operational medium, defined as the aerospace. Recall that General Thomas White first defined the aerospace in 1958 and said that "air and space comprise a single continuous operation field in which the Air Force must continue to function" [6:2-1]. Our thrust is that environmental doctrine must consider space as part of the operational environment, and

not as a specific mission. Others may argue, and justifiably so, that space is a unique environment, just as different from the endoatmosphere as the ocean environment is from the air. From this perspective, one could easily contend that space doctrine should not be linked in any way to Air Force doctrine, which emphasizes military air operations.

A second limitation is that we were unable to clearly discriminate between various elements at some of the levels in our hierarchy. As we will show, in some cases it is difficult to discriminate between tasks and missions, tasks and requirements, or even requirements and missions. The MSSTP hierarchy had the same problem. We believe this is an inherent limitation with modeling the military environment from a mission needs perspective. In some cases, what are described as tasks may be primary missions to support military goals. The specific delineations between these elements are dynamic and depend on the scope and nature of the problem under consideration. Thus, we feel the hierarchy is useful as a general framework, but that users may have to tailor it somewhat to fit their particular needs. We will point out some examples of this somewhat paradoxical situation when we discuss missions, tasks, and requirements.

Finally, we note that after we developed our hierarchy the Air Force revised AFM 1-1, "Functions and Basic Doctrine of the United States Air Force" [7]. It corrects many of the problems we noted with the old AFM 1-1 [6] and is more

representative of basic or fundamental doctrine. A major change is that the new doctrine dropped Space Operations as an Air Force mission. We do the same in our hierarchy. Where applicable, we have referenced both the new and old Air Force published doctrine in the discussion that follows.

The Hierarchy

The hierarchy we propose is shown in Figure G-2. We also show the connectivity between technology issues and the scientific-technological instrument of national power for completeness. We already discussed the higher levels of the hierarchy (national interests, national objectives, national policies and instruments of national power) in some detail in Chapter Five. Our interest here is in describing the levels of the mission needs hierarchy in greater detail. This hierarchy is shown under the military instrument.

The Military Instrument. The military is one of the instruments of national power. The national leadership determines when and how the military instrument is to be applied in support of national objectives and policy. Since our interest is with the Air Force, we deal only with this Service in our hierarchy. However, we have incorporated DoD space-related areas in the hierarchy to ensure we represent all military requirements in the space medium.

Fundamental Military Objective. The old AFM 1-1 listed four fundamental military objectives: sustain deterrence, assure territorial integrity, conduct warfare, and

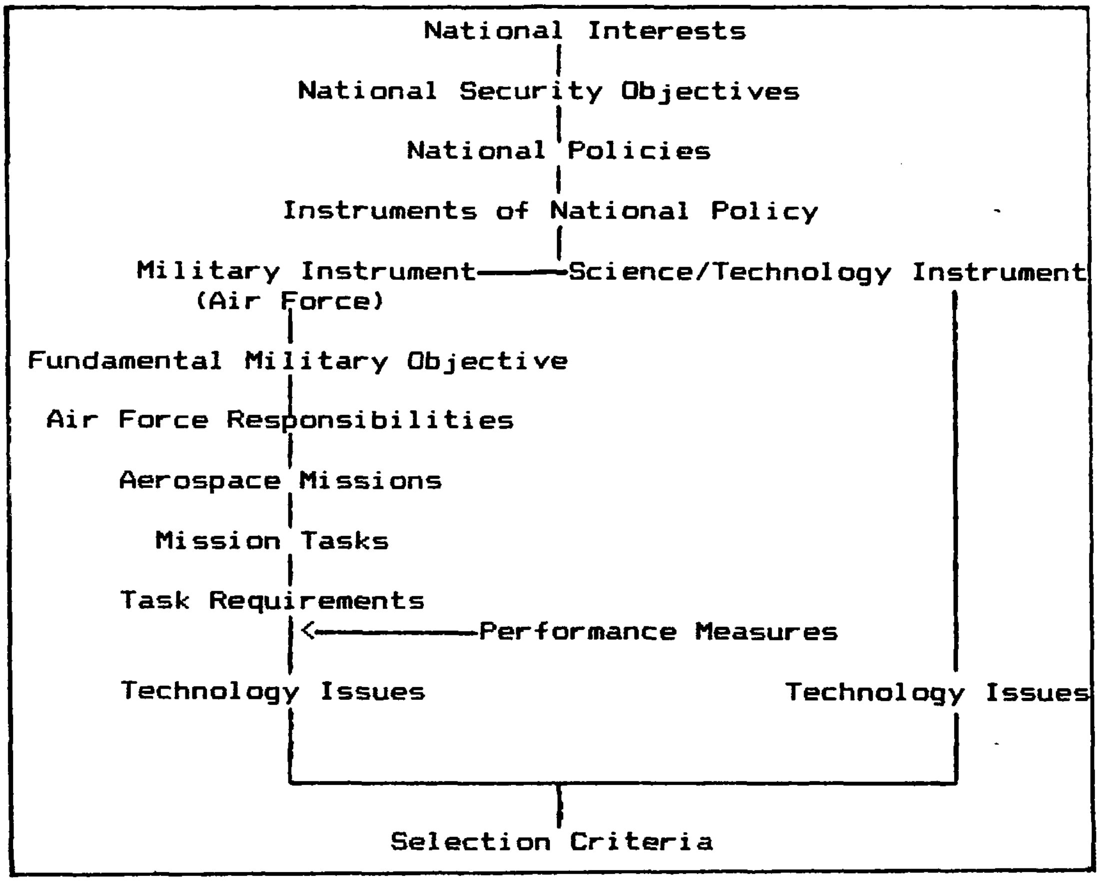

Figure G-2. Space R&D Advocacy Hierarchy

resolve conflict quickly and on terms favorable to the United States. The new AFM 1-1 changed these somewhat, reducing the list to three. These are [7:1-2]:

> 1. Deter attacks against the United States, our allies, and against vital US interests worldwide, including sources of essential materials, energy, and associated lines of communication.
>
> 2. Prevent an enemy from politically coercing the United States, its allies, and friends.
>
> 3. If deterrence fails, fight at the level of intensity and duration necessary to attain US political objectives.

For the sake of clarity, we reduced these elements to one fundamental military objective: Resolve conflict

quickly and on terms favorable to the United States. Sustain deterrence and assure territorial integrity are more appropriately defined as national security objectives or interests. Inherent in deterrence and preventing coercion is having the necessary force structure to resolve conflict. If you do not have a strong enough force structure, then you cannot be expected to deter a potential adversary from taking aggressive or coercive action against you. Conducting warfare is implied in our definition of the fundamental military objective.

Air Force Responsibilities. These are major functions assigned to the Air Force by law and DoD directives. AFM 1-1 [6] lists several sources from which these major responsibilities are derived. They include: the National Security Act of 1947; the National Aeronautics and Space Act of 1958, which identifies the Air Force as the DoD Executive Agent for space; JCS Pub 2, "JCS Unified Action;" and DoD Directive 5100.1, "Functions Paper" of 1958. The major role of the Air Force is to conduct aerospace operations in support of the national interest of the United States. AFM 1-1 [6] lists eight primary and three collateral functions [6:2-1,2-2]:

1. Conduct prompt and sustained combat operations in the air to defeat enemy airpower;

2. Formulate doctrine and procedures for the organizing, equipping, training, and employment of Air Force forces;

3. Provide forces for strategic air warfare;

4. Provide air transport for worldwide deployment;

5. Provide adequate, timely, and reliable intelligence;

6. Furnish close combat and logistical air support to the Army, to include: airlift, support, and resupply of airborne operations; tactical reconnaissance and aerial photography; and interdiction of enemy lines of communication;

7. Provide aerial photography for cartographic purposes;

8. Coordinate with and support other Services in developing: doctrines and procedures for the unified defense of the US; doctrines, procedures, and equipment for air defense of land areas; tactics, techniques, and equipment for amphibious operations; doctrines, procedures, and equipment for airborne operations;

9. (Three collateral functions) Train forces to: interdict enemy sea power; conduct antisubmarine warfare and to protect friendly shipping; and conduct aerial mine-laying operations.

We reduce thi. list to seven major responsibilities. The major changes were to incorporate like areas into the same function (i.e. all references to photography are listed under a single responsibility) and to incorporate environmental doctrine in our definitions. A weakness with listing these functions is that many do not appear to be on the same level (some appear to be more likely candidates for specific tasks than broad Service responsibilities). However, our primary intent is to show how a mission needs hierarchy could be developed taking environmental doctrine into consideration. Since we are not specifically defending the elements comprising each level, we show our representative list of major responsibilities below. These are:

1. Provide forces to conduct prompt and sustained combat operations in the aerospace to defeat enemy air and space power. In order to maintain freedom of action throughout the aerospace medium, we must have forces capable of securing and maintaining control of this critical operational environment. We must be capable of denying the same freedom of action to any potential enemy. While current treaty obligations and international law preclude the employment of offensive weapons of mass destruction in space, our doctrine and future strategy options must incorporate the exoatmospheric regions of this operational medium in planning and force employment tactics. Only in this fashion can we be prepared to conduct warfare throughout all possible warfighting environments. To not do so concedes the space arena to the enemy.

2. Provide forces for strategic aerospace warfare. Our highest defense priority is to deter strategic nuclear attack on the United States or its allies. A key element to successful deterrence is possessing and demonstrating the capability to fight and exact such damage on an enemy to dissuade him from initiating a strategic nuclear attack. Currently the nuclear triad forces provide this capability. While international law and treaty obligations prohibit us from deploying weapons of mass destruction in space, our doctrine and future strategies must consider and plan for this contingency. An integral aspect of strategic warfare is adequate warning of attack to provide the capability to

launch counterattacks, survive attack, and reconstitute forces. Space-based systems significantly contribute to this warning capability.

3. <u>Provide adequate, timely, and reliable intelligence, surveillance, reconnaissance, and aerospace photography</u>. This function consolidates three functions listed in AFM 1-1: tactical reconnaissance and aerial photography; provide adequate, timely, and reliable intelligence; and provide aerial photography for cartographic purposes. It also recognizes our capability for performing these functions from exoatmospheric platforms by redesignating the operational environment from aerial to aerospace. The functions of intelligence, surveillance, and reconnaissance support to some degree all other functions and Air Force missions. Without accurate intelligence, reliable surveillance and responsive reconnaissance, our forces cannot be expected to sustain deterrence or resolve conflict.

4. <u>Provide the capability to interdict enemy targets</u>. This function consolidates the following functions listed in AFM 1-1: interdict enemy lines of communication and the collateral functions of interdiction of enemy sea power and conduct mine-laying operations. To resolve conflict on terms favorable to the United States we must be capable of conducting warfare across the entire conflict spectrum. To support this objective, we must be capable of destroying or inflicting damage on enemy targets in all mediums (land, sea, and aerospace) and disrupt enemy lines of communica-

tion. We must foresee the possibility of extending interdiction capability to the exoatmospheric regions to negate or destroy enemy capabilities in this environment.

5. Provide forces for aerospace defense of US and allied territories and resources. This function incorporates the space responsibilities of conducting needed defensive operations to protect our use of space and conducting space operations to protect US resources from threats in and from space (listed in AFM 1-6 [8]) with the AFM 1-1 function of equip for air defense of land areas. This defense function directly supports the national objectives of assuring territorial integrity and sustaining deterrence by contributing to our capability to resolve conflict. We must be prepared to defend critical assets and territory in all operational media, including space. Many of our indications and warning systems, surveillance and reconnaissance platforms, and crucial communications systems are space-based and protection of these assets is tantamount to successfully deterring and countering enemy attack. Our environmental doctrine must consider innovative tactics and strategies for protecting these space-based assets, as well as consider the potential for protecting key land areas from space-based defensive weapons platforms.

6. Formulate doctrine and procedures for the organizing, equipping, training and employment of Air Force forces. This major responsibility is basically unchanged from that listed in AFM 1-1.

7. <u>Coordinate with and support other Services in joint operations and strategy</u>. This, too, is basically unchanged from AFM 1-1.

<u>Aerospace Missions</u>. AFM 1-1 lists nine primary missions, one collateral mission, and various functions (specialized tasks) that the Air Force performs in support of its primary responsibilities. The primary missions are: strategic aerospace offense; space operations; strategic aerospace defense; airlift; close air support; air interdiction; counterair operations; surveillance and reconnaissance; and special operations. The collateral mission is described as operations against enemy naval operations while the other functions are intelligence, command and control, communications, indications and warning, data processing, environmental monitoring, and aerial refueling. Most of the missions listed have sub-elements that further describe or specify the missions.

A key concern we had with the list is that space operations is broken-out separately from other Air Force missions, despite the fact that AFM 1-1 acknowledges that space is an environment in which the Air Force must operate. There is one notable exception. Space defense is listed in conjunction with strategic aerospace defense. Under the space operations mission are listed two types of operations: space support and force enhancement. We disagree with designating force enhancement as a mission support element. Any system or capability deployed is essentially an

"enhancement" over previous systems or capabilities, irrespective of the environment the system is designed to operate in.

We believe that another mission ordering is appropriate and better represents space as an integral part of the operating environment of the US Air Force. By consolidating aspects of certain missions, renaming several, and deleting a few, we came up with the following list of eight missions: strategic aerospace offense; strategic aerospace defense; aerospace lift support; close aerospace support; aerospace interdiction; counteraerospace operations; special operations; and surveillance and reconnaissance. The following points describe each of these suggested missions and identify changes made to the structure currently in AFM 1-1. Note that all incorporate, or could incorporate operations in space.

1. Strategic Aerospace Offense. This mission is retained with no changes over what is listed in AFM 1-1. Strategic aersopace forces act as a deterrent to nuclear war. They represent the capability to inflict such damage on a potential nuclear enemy so as to make the idea of nuclear warfare unacceptable for any side to initiate. To be a credible deterrent, these forces must be capable of surviving attack, reconstituting forces, and preserving a sufficient attack capability so as to inflict devastating losses on an attacking enemy. Strategic offensive forces must be capable of penetrating enemy defenses and delivering

nuclear weapons accurately against assigned targets.

In addition to weapons delivery systems and penetration aids, other requirements exist that are essential to support this mission. Strategic offensive forces must have sufficient warning to disperse and/or launch counterattacks and survive initial attacks. Command, control, and communications, data processing and navigation aids must be responsive, reliable in a nuclear environment, secure, redundant and/or survivable. While international law currently prohibits deploying weapons of mass destruction in space, it is technologically feasible to do so and would provide an alternative to add to the existing triad that would present unique and perplexing challenges to a potential enemy's defensive forces.

Certain "force enhancement" capabilities listed in AFM 1-1 under space operations potentially apply to strategic aerospace offense. They include: conduct global surveillance, worldwide command and control support, provide precise positioning and navigation data, and present timely and detailed meteorological information.

2. Strategic Aerospace Defense. This mission is unchanged from that listed in AFM 1-1. AFM 1-1 already incorporated space defense as an integral element of the total strategic aerospace defense mission. This mission enhances deterrence by denying and/or nullifying hostile acts in or through the aerospace. To protect national sovereignty during peacetime, crises and war, strategic

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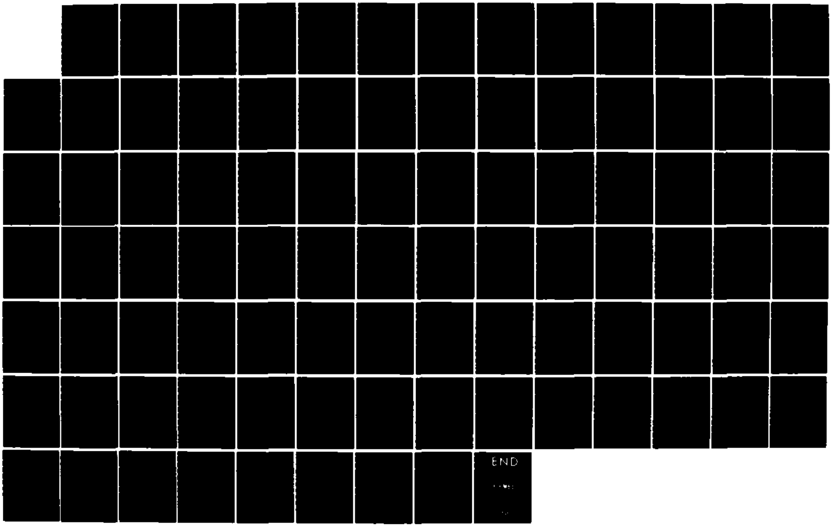

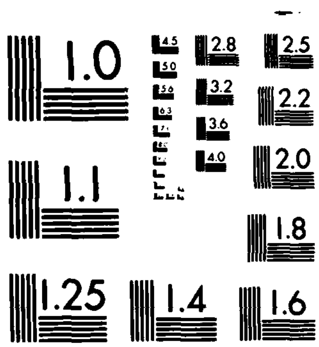

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NATIONAL BUREAU OF STANDARDS-1963-A

aerospace defense must detect, identify, intercept and destroy hostile vehicles attempting to penetrate our aerospace and do this mission under all meteorological conditions. It must provide adequate warning and assessment of strategic attack and tactical warning to the national command authorities. Defense forces must be capable of protecting the territory of the US and its allies, as well as critical resources on the land, sea, or in the aerospace. Warfighting defensive systems must be flexible and highly responsive to be capable of neutralizing threats. We have incorporated the following collateral missions listed in AFM 1-1 under operations against enemy naval forces: defend friendly naval forces and engage in anti-submarine warfare. The task of delivering mines supports this mission.

Exoatmospheric systems offer tremendous potential for future aerospace defense capabilities. For example, the capability to detect and destroy nuclear warheads before they reenter the atmosphere is one particular mission addressed by the SDI concepts.

Critical to the successful accomplishment of this mission is a capability to detect, track and identify all objects in the aerospace. To be fully effective, strategic aerospace forces must be able to discriminate between actual targets and possible decoys or background "clutter." Effective command and control is absolutely essential. Battle management systems must be capable of acquiring targets, destroying or negating them, and confirming target destruc-

tion or misses in time to attack the target again or pass responsibility for its destruction to another defensive element.

The following "force enhancements" may have applicability: conduct global surveillance, enable worldwide command and control, provide precise positioning and navigation data, and present timely and detailed meteorological information. From space support (we show this under Aerospace Lift Support) satellite surveillance and control is likely to be a supporting factor, as would on-orbit support for space-based defensive systems.

3. Aerospace Lift Support. This mission was originally designated "airlift" in AFM 1-1. It included both strategic and tactical airlift, providing a capability to deploy forces to any part of the world and support them there. Airlift embodies a key facet of a fundamental Air Force capability -- rapid, long range mobility. Comprised of both military and civil contract aircraft, the airlift mission directly supports or provides: employment operations, strategic and tactical deployment of combat forces and equipment, logistics support, and aeromedical evacuation. We have changed the name of this mission to reflect supporting the same or similar capabilities in space. We have consolidated space support, listed in AFM 1-1 as one of three distinct space responsibilities, with airlift to form the Aerospace Lift Support mission. In addition to traditional (endoatmospheric) roles, aerospace lift support must

provide launch and recovery support for space payloads, on-orbit support of space platforms, and satellite surveillance and control. As we expand into space, our scope of responsibility to support space-based systems will also expand. Resupplying manned platforms, evacuating injured or ill space personnel, providing orbital maintenance and replacement, and controlling space platforms are a few of the many tasks which may have to be accomplished in space.

In addition to improvements necessary to support our worldwide deployment of forces capability (inter/intra theater airlift aircraft capable of transporting existing weaponry and forces) we must be able to launch payloads of varying mass into space into a variety of orbits and inclinations. This could entail a capability for transferring payloads from low earth orbit to geosynchronous, constructing large platforms in space, storing highly corrosive and/or dangerous reactants in space, supporting a manned presence in space, and many other potential roles. Navigation aids, survivable and secure communications, and command and control support will be essential to support this mission.

4. Close Aerospace Support. Listed in AFM 1-1 as close air support, we have changed the mission description to include the space environment as well. AFM 1-1 mentions that close air support involves air attacks against hostile targets that are in close proximity to friendly forces. It may be used to support offensive or defensive operations by

friendly forces. Close air support requires access to the battlefield, accurate weapons delivery, and target coordination between surface and air forces. Close air support enhances surface force operations by providing a wide range of weapons and greater mass at decisive points; flexibility, shock, innovation, and surprise; and firepower, maneuver, and flank protection. We have also incorporated the capability to neutralize or destroy enemy naval forces, which is listed as one of the collateral missions in AFM 1-1 under operations against enemy naval forces. While it may be difficult to imagine any near term close "space" support role where space fighter bombers attack enemy space forces, some people have already suggested how space-based weapons could be used to support surface operations. Again, for reasons mentioned earlier, we should not close the door on future possibilities in supporting this mission either in space or with space-based systems.

The most likely applications for space support of this mission would appear to be space-based weapons providing pin point delivery on enemy positions in supporting friendly surface or naval forces (space-based defense of space systems falls under another mission category). To accomplish this mission would require precise navigational, command, control, and communications, and data processing systems; extremely accurate pointing and tracking capabilities; a complete understanding of atmospheric interactions with whatever weapon kill mechanism is used; and many others.

Frankly, in the foreseeable future, the major role for space in supporting this mission will probably be providing ground and air forces with precise navigational information, reliable and responsive communications/data links, and meteorological data from space-based platforms. Costs and critical operational concerns would seem to dictate that this mission can be more effectively conducted with endoatmospheric systems at the present time.

5. <u>Aerospace Interdiction</u>. This mission was defined as "air interdiction" in AFM 1-1 and related to operations conducted against an enemy's potential before it could be effectively used against friendly surface forces. Its goal is to prevent enemy forces from sustaining an effective level of combat and to deny them their military objectives. In this respect, aerospace interdiction would extend these same responsibilities for interdicting enemy capabilities in space before they can be used against friendly space or earth-based forces and resources. Aerospace interdiction requires a capability to attack fixed, moving, and movable point and area targets. Targets would include enemy lines of communication; enemy supplies; and unengaged enemy forces in rear areas. Interdiction missions could also include attacks against an enemy's uncommitted naval forces. For this reason we have also included the capabilities to neutralize or destroy enemy naval forces, engage in anti-submarine warfare, and deliver mines, which were listed in AFM 1-1 under the collateral mission operations against

enemy naval forces.

To effectively interdict enemy targets, friendly forces must know the target location, environmental conditions, and enemy defenses; be able to counter enemy defenses; and acquire, track, and destroy targets. These requirements identify the need for accurate intelligence, surveillance, reconnaissance, command and control, pointing and tracking accuracy, electronic countermeasures and counter-counter measures, and weapons systems (delivery platform and kill mechanisms) capable of destroying designated targets.

Extending interdiction capabilities in space is logical. As potential enemies become more dependent on space systems to support their warfighting capabilities, these systems become more lucrative targets. Since we must be prepared to fight at any level in the conflict spectrum, we need to consider requirements for an interdiction capability in space. Additionally, many of the technologies required to support air-to-ground missions (weapons acquisition and tracking sensors, guidance systems, etc) also support space requirements. Space-based systems obviously could play an important support role by providing the navigation, communications, intelligence, and reconnaissance support required for aircraft to effectively carry out an air-to-ground interdiction mission.

6. <u>Counteraerospace Operations</u>. This mission is defined in AFM 1-1 as "counterair operations." We extended the operational environment to include space. Given that

the ultimate goal of counterair operations is to gain and maintain air superiority, counteraerospace operations would be conducted to gain and maintain superiority in the space region as well. Aerospace supremacy is a condition that gives friendly forces freedom of action throughout the area of conflict and at the same time denies the enemy the same freedom. This is accomplished by destroying or neutralizing the enemy's offensive and defensive aerospace capabilities.

Counterair operations were broken out in three distinct areas: offensive and defensive counterair and defense suppression. The same areas apply to aerospace applications.

Offensive counteraerospace systems must be designed to seek out and destroy the enemy's offensive counteraerospace systems and support facilities in order to gain supremacy in the aerospace medium.

Defensive counteraerospace operations are tasked to deny the enemy the freedom to carry out offensive operations, and to defend supply lines, protect friendly bases, and support land and naval forces. To fulfill these roles counteraerospace forces must be capable of detecting, identifying, intercepting, and destroying enemy aerospace forces.

Defense suppression is designed to degrade, neutralize, or destroy the enemy's aerospace defense and command and control systems. In this regard, defense suppression directly supports offensive and defensive counteraerospace operations by inhibiting (using lethal or nonlethal meas-

ures) enemy capabilities for defensive actions. Electronic warfare, electronic counter measures, and electronic counter-counter measures are frequently the mechanisms for accomplishing this mission.

To accomplish counteraerospace missions, we must not only have capable weapons platforms and systems, but acquisition and tracking, electronics, communications, precise positioning, environmental monitoring, data processing, and intelligence capabilities as well.

Maintaining freedom of action in space is a national security objective, so it is not difficult to justify incorporating the space environment in this traditional Air Force role. The need to possess supremacy in space is obvious -- we rely so much (totally in some cases) on space-based systems to provide attack warning, intelligence, and communications that we cannot afford to put them at risk to enemy space-based attack.

7. <u>Special Operations</u>. Special operations forces support the unified commanders at the direction of the NCA. These operations are carried out by specially trained and equipped forces from each Service as a team in support of US security objectives. Special operations, which are undertaken in enemy controlled or politically sensitive territory, cover a broad spectrum of actions and are conducted at every level of conflict. Unconventional warfare, foreign internal defense, and psychological warfare are examples.

To accomplish the variety of tasks required by this mission description, forces must have secure and responsive communications, command and control, reconnaissance and intelligence. Space systems provide many of these capabilities. While it may be difficult to conjecture conducting special operations in the space environment anytime in the near future, space-based platforms will certainly continue to support these types of missions.

8. Surveillance and Reconnaissance. Although AFM 1-1 lists surveillance and reconnaissance as a mission, both can be defined as "functions" as well. We use manned and unmanned aerospace vehicles, as well as land-based sensors, to carry out strategic and tactical surveillance and reconnaissance. These operations provide early warning of enemy actions and other information vital to the NCA and field commanders. They help identify enemy capabilities and force structure. Surveillance systems collect information continuously from the aerospace and from the earth's surface and subsurface. They provide information on enemy attacks, including their source, nature, and size. They predict the impact point of missile warheads. They tell us the location and timing of nuclear detonations and other attack assessment data.

Reconnaissance missions are directed towards localized or specific targets. Through these missions a variety of data are collected, including meteorological, hydrographic, geographic, electronic, and communications characteristics

on any given area of the earth's surface. Together, surveillance and reconnaissance provide information on the activities and resources of any potential enemy.

Surveillance and reconnaissance support both strategic and tactical arenas. Strategic surveillance and reconnaissance support our needs for national and strategic intelligence, allowing us to assess the total capability of a foreign nation to wage war and monitor the progress of a war. Tactical operations support the theater and the tactical field commanders. They provide indications of hostile intent, plus information from which intelligence is derived. We have also incorporated the collateral mission of providing surveillance and reconnaissance support in operations against enemy naval forces under this mission.

Strategic surveillance and reconnaissance systems must allow us to: identify targets for strategic and tactical attack; provide indications and warning of hostile intent and actions; assess damage to enemy and friendly targets; determine force structure; determine our requirements for R&D of warfighting systems; and help verify compliance with treaties and agreements. Additionally, they provide information that assists the military authorities in analyzing and developing tactics to counter enemy deployment and employment. Tactical systems provide information on: the disposition, composition, and movement of enemy forces; the location of enemy lines of communication, installations, and electronic emissions; post-strike damage; conditions in

surface battle areas; and weather and terrain.

Space-based systems have been invaluable in supporting surveillance and reconnaissance missions. Not only are space-based systems more capable than many other systems (in some cases they are the only systems that can provide required capabilities), they often are more economical. We depend heavily on these systems to provide indications and warning of attack and communications with our strategic forces. These assets are vulnerable to various enemy countermeasures, including ground-based laser blinding, jamming, and even destruction by enemy anti-satellite systems.

This concludes our discussion of aerospace missions. We have shown how redefining missions to include space as part of the operational environment still gives full coverage t all mission areas. It also allows R&D and mission planners to be broader scoped in considering future military requirements. In the next section we discuss military tasks that can be performed or supported by space-based system_ These tasks directly link to the missions we have j_.-+ discussed.

<u>Tasks</u>. Tasks are defined as those :pecific capabilities required to accomplish missio.._ We used the task list developed in the MSSTP _.- a point of departure for our task list. In m_.-+ cases we differ very little in substance from the tas.- defined in the MSSTP. We have separated tasks into eight general groupings.

1. Reconstitution of Forces. This is a fairly specific task supporting primarily the strategic aerospace offense mission. It addresses the requirement for regrouping and tasking strategic offensive forces after an initial attack. This task places considerable demands on communications and data processing functions, among others.

2. Launch and Recover Space Platforms and Payloads. This obvious task is necessary to deploy any space-based system. The requirements of the system (mass, volume, orbit, etc) will determine the specific performance level required of this task.

3. Detect, track, identify, intercept, and destroy targets. This general task could easily be further broken down into separate task categories. Since this is a rather obvious option, we show it as a single task to indicate that sometimes these individual tasks may overlap or be combined into a synergistic whole. Normally we would expect this task to be further defined by the type of target. These include: intercontinental and submarine launched ballistic missiles; air vehicles; surface targets (land and sea based); and space vehicles and platforms.

This task category replaces such MSSTP tasks as: indicate and warn of attack from ballistic missiles/SLBMs, air vehicles, space vehicles and platforms; discriminate targets from background and enemy deception; detect nuclear detonations by size and location; predict impact points of ballistic missiles; and perform damage assessment following

tactical or strategic attack.

4. Provide on-orbit support. This support task is essential to most space-based systems. It can be performed in a variety of ways (ground-based control, space-based maintenance, etc). We also include refueling, a specialized task listed in AFM 1-1, in this category. Future space systems may depend on periodic refueling and maintenance from space support depots.

5. Penetrate enemy defenses. This task depends on the vehicle used to penetrate defenses, as well as the nature of the defense. Types of vehicles of interest to space planners are: ballistic missiles/SLBMs, air vehicles, and space-based platforms and vehicles.

6. Environmental Monitoring. Environmental information is an essential factor in planning and conducting air and surface operations. During wartime, weather information becomes an integral part of the decision process in employing forces, selection of weapons systems, routes, targets, and delivery tactics. The MSSTP defined environmental monitoring as a function (see task requirements, below). However, we believe this is more accurately described as a task that directly supports a variety of missions. It also requires a variety of "functions" to support it depending on the specific capabilities called for in the task.

7. Electronic Warfare. Electronic warfare is used to counter, deceive, or destroy the enemy's use of the electromagnetic spectrum during offensive or defensive operations.

It operates in three dimensions: electronic warfare support measures, electronic counter measures, and electronic counter-counter measures. Targets are usually command and control systems, radar and fire control systems, communications systems, infrared and electro-optical systems, and navigational aids. There are many obvious applications for electronic warfare in space. As a task it can directly support many of the missions discussed earlier.

8. <u>Command, Control, and Communications</u>. We break this out as a task category, although the MSSTP does not include it here. Command, control, and communication systems provide commanders with reliable, rapid, survivable, and secure communications networks to command and control forces. These networks depend on networks of intelligence, indications and warning, communications, data processing, environmental services, and trained personnel. They allow the commander to coordinate the planning, direction, and control of all forces and operations. They also provide commanders the status and capabilities of their forces as well as those of the enemy. They can direct the targeting of weapons and the tactical advantage inherent in shock action and maneuver. Command, control, and communications are essential in supporting every mission category discussed earlier.

<u>Task Requirements</u>. These are the basic building blocks or specific capabilities that help to further define task performance levels. Tasks may require one or more of these

building blocks. They are called "functions" in the MSSTP, which listed 15 (Appendix C). Our list is much less, since we described space operations (launch and recovery of payloads and platforms) and environmental monitoring as tasks. The five general categories of task requirements we define are discussed below.

1. Communications. Depending on task and mission requirements, communications may be defined by several of the following characteristics: accuracy, availability, capacity, flexibility, interoperability, timeliness, jam-resistance, mobility, reliability, security, speed, and survivability.

2. Data Processing. The MSSTP did not list this as a function; however, we believe it is an important "building block" to support numerous tasks. Characteristics include: memory size, processing speed, hardening, access, software, timeliness, and capability (type and number of specific functions it must support or perform).

3. Navigation. This task requirement can be characterized by positioning accuracy required (in three or less dimensions), speed of vehicle or target, direction, heading accuracy, and timeliness.

4. Detection. The MSSTP titled this surveillance and broke it out into five separate "functions": air vehicle detection and track; ballistic missile detection and track; nuclear detonation, detection, and location; space vehicle detection and track; and surface target surveillance/recon-

naissance. We felt these were more accurately described as tasks. However, we do agree that detection should be listed as a task requirement since it will determine the type of sensors employed and performance required of the sensor. Characteristics include, among others: field of view, resolution, number of targets capable of discriminating, sensitivity, power, and tracking time.

5. Force Application. This most necessary task requirement defines the types of weapon systems and capabilities required to support many of the tasks. We further categorize force application according to the target to be destroyed or neutralized: air vehicle destruction, ballistic/SLBM missile destruction, space vehicle or platform destruction, and surface target (land and sea) destruction. Characteristics are a function of the target, employment tactics, defenses, weapons platform, and the physical environment. Specifics include: energy required on target for destruction, range, countermeasures, timeliness, kill verification, and power requirements.

Performance Parameters. While not actually part of the hierarchy, we show performance parameters as an integral factor in determining performance requirements to meet missions and tasks. The MSSTP identified six candidate parameters to be used to further define specific task performance requirements. These are listed below.

Coverage: Geographical boundaries over which the functions must be performed.

Capacity: The number of units served, detected, identified, tracked, etc. The number of messages, units, or bits transmitted or received per second.

Quality: Quantitative measures of the distinguishing attributes such as location accuracy, probability of detection, false alarm rate, probability of correct message receipt, track accuracy, probability of kill, etc.

Timeliness: Allowable system time delays or response times such as allowable time from event detection to message transmission of event detection.

Availability: Percentage of time the system must be in position and able to accomplish the assigned task.

Survivability: Endurance requirements imposed by the military mission or task. Specified in terms of duration (minutes, hours, days, years) a function must be available to accomplish the associated task.

Technology Issues. The final level of our hierarchy that we discuss here is technology issues. The performance attributes discussed above allow planners to determine specific performance needs for military tasks. If existing technology cannot provide required performance levels, then a technology issue is defined. If planners have done their job well, then the performance deficiencies become the technology issues. Otherwise, technology issues can be identified in any number of ways, including: system concepts, paper studies, experimentation, laboratories, industry, etc. Regardless of how technology issues are generated, they can easily be linked to this hierarchy to determine the extent of their contribution to satisfying mission accomplishment, if the technology issue were satis-

factorily resolved.

Limitations Of and Uses For the Hierarchy.

We note here that discriminating between missions, tasks, and in some cases task requirements ("functions") is dependent entirely upon the scope and nature of the problem under consideration. Some of the tasks we describe could appear to be missions. As we mentioned in the introduction, our inability to define a set of collectively exhaustive, mutually exclusive tasks is a limitation with this hierarchical structure. However, the MSSTP has the same problems. As we pointed out in Chapter Five, with complex real-world problems, it is usually impossible to completely break out hierarchical levels and even distinguish between elements.

Nonetheless, we believe this model is still useful for long range mission and R&D planners and also for system designers. It can be used as a structure for considering options, defining requirements, and specifying performance deficiencies.

Linkages are easily derived between the various levels and elements within each level. This information is especially useful for mission area analyses, where weights can be assigned to the various elements and levels based on relative importance to a predefined goal. We show in the following example one such linkage that tracks from one of the Air Force responsibilities through missions, tasks, and task requirements.

Consider the responsibility of "provide forces for strategic aerospace warfare." Several missions support this broad responsibility, including: strategic aerospace offense, surveillance and reconnaissance, aerospace defense, aerospace interdiction, and special operations. Analyzing one of these missions (strategic aerospace defense), we see that a number of tasks can be linked to it. In this case, we select the following tasks as applicable to strategic aerospace defense: launch and recover space platforms and payloads; provide on-orbit support; detect, identify, track, and destroy ballistic missiles, air vehicles, and space vehicles and platforms (includes also prediction of impact points of ballistic missiles, discriminate targets from background and deception, perform damage assessment, and detect nuclear detonations); electronic warfare; command, control, and communications; environmental monitoring; and penetrate enemy defenses with anti-ballistic missiles, air vehicles (fighter interceptors), and space-based weapons. Analyzing one of these tasks (command, control, and communications) with respect to task requirements helps further define the specific performance required of the task to meet mission requirements. This task must be supported by communications, data processing, detection, and possibly navigation. Selecting one of these task requirements and evaluating it against the six performance parameters will help to clearly define specific performance needs required of the task requirement to ultimately meet mission require-

ments. Obviously the mission requirement must be clearly specified to begin with in terms of threat, numbers, defenses, etc. Often this is the most difficult task in the entire analysis.

Appendix H: Funding Curves

It may be necessary in the space technology advocacy problem to determine the budget impacts of decisions. However, as we pointed out in Chapter 2, getting accurate cost estimates of R&D programs is at best a risky business. On the other hand, it may be possible to do some "what if" analysis by displaying possible funding curves to the decision maker. In this way, the decision maker can specify the time, the overall dollar value of the programs, and pick an appropriate shape of the funding curve. From this a suitable computer program can calculate the yearly funding requirements for the program. Again, we stress that this is but a tool to aid the decision maker in gaining further insight into the impact of his decisions. However, the accuracy of the cost estimates is indeed uncertain. Because of this, this type of analysis should be accompanied by a great deal of sensitivity analysis.

On the next page is an example of a funding curve. The decision maker would be prompted for the total time and total budget for the program. He would also be required to specify the percentage of the total budget that would be needed in each quarter of the total time.

The decision maker specifies the total time and total budget for this funding profile. He also specifies the 25%, 45%, 20%, and 10% of the total budget for each quarter of the total time.

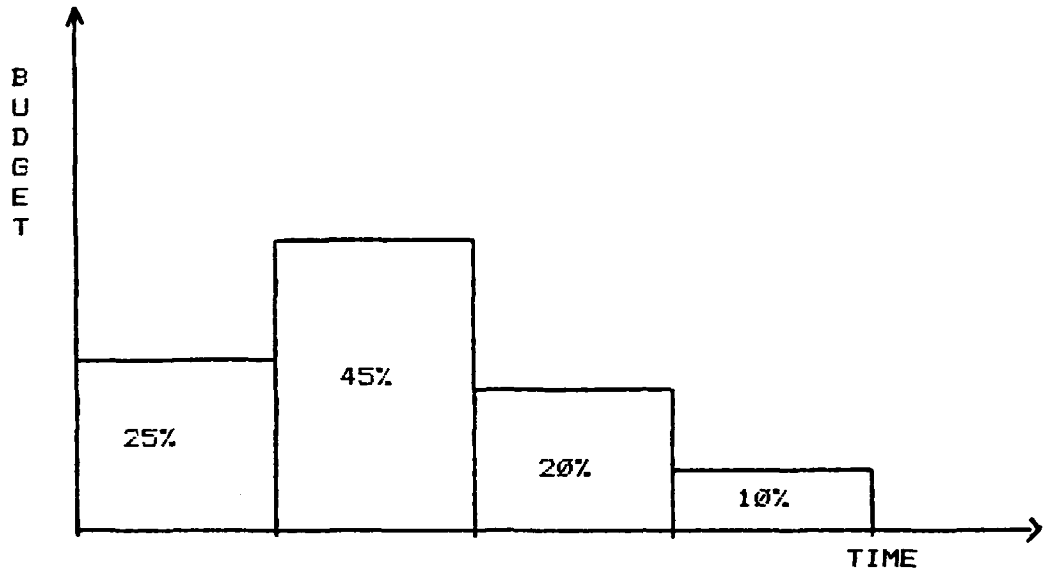

Figure H-1. Sample Funding Curve

For example, if the total budget was specified as $1,000,000 for a four year program, then for the first year $250,000 would be needed, the second year would need $450,000, the third year would need $200,000, and the final year would require $100,000.

The level of sophistication (i.e., the number of possible funding curves and the fine tuning of time and budget) can always be increased. However, from our research of the literature (in Chapter Two), simple techniques such as the one described above are probably adequate to pursue "what if" types of analyses. The decision maker should be involved in specifying the types of budget curves that are most appropriate for this type of analysis. The emphasis once again should be on decision support. These curves should aid the decision maker in performing "what if"

analyses. These funding curves could be an additional analytical tool in the decision support methodology for space technology advocacy.

Appendix I: Analytic Hierarchy Process Calculations

This appendix briefly describes the mathematical calculations required to determine a priority vector from a positive reciprocal matrix. The reader should refer to Saaty [198; 203] for the theoretical development of the analytic hierarchy process.

A postive reciprocal matrix is a square matrix having the following properties:

Let matrix A = a(i,j) where i,j = 1,...,n

Property 1: a(i,j) > 0 for all i,j = 1,...,n

Property 2: a(i,j) = 1/a(j,i) for all i,j = 1,...,n

It is easy to demonstrate that these two properties define a positive, reciprocal, square matrix.

To determine the priority vector for a given positive, reciprocal matrix, the principal eigenvector is computed. One begins with a matrix A of real numbers, representing the pairwise comparisons of the importance of the elements of one level in the hierarchy with respect to one element of the next higher level, and finds the largest eigenvalue and determines the solution of the equation

$$Aw = (\lambda \max)w$$

where (λ max) is the largest eigenvalue. The priority vector is the vector w after w has been normalized. Although computer solution is the preferred method [203:19], Saaty identifies four methods to approximate the priority vector. These are repeated here [203:19].

1. (The crudest) Sum the elements in each row and normalize by dividing each sum by the total of all the sums, thus the results now add up to unity. The first entry of the resulting vector is the priority of the first activity; the second of the second activity and so on.

2. (Better) Take the sum of the elements in each column and form the reciprocals of these sums. To normalize so that these numbers add to unity, divide each reciprocal by the sum of the reciprocals.

3. (Good) Divide the elements of each column by the sum of that column (i.e., normalize the column) and then add the elements in each resulting row and divide this sum by the number of elements in the row. This is a process of averaging over the normalized columns.

4. (Good) Multiply the n elements in each row and take the nth root. Normalize the resulting numbers.

To obtain an approximate value for the consistency of the matrix:

1. Multiply the matrix of comparisons (A) on the right by the estimated solution vector (found in one of the four ways above or by computer). This results in a new vector.

2. Divide the first component of this new vector by the first component of the estimated solution vector, the second component of the new vector by the second component of the estimated solution vector and so on. This results in yet another vector.

3. Take the sum of the components of this third vector and divide by the number of components (n). This is an approximation to the number (λ max) called the maximum or principal eigenvalue. This number is used in estimating the consistency as reflected in the proportionality of preferences. The closer (λ max) is to n (the number of activities in the matrix) the more consistent is the result.

4. Deviation from consistency may be represented by

$$(\lambda\ \text{max} - n)/(n-1),$$

which is called the consistency index (C.I.).

5. The consistency index of a randomly generated reciprocal matrix from the scale 1 to 9, with reciprocals forced, is called the random index (R.I.). The ratio of C.I. to R.I. for the same order matrix is called the consistency ratio (C.R.). A consistency ratio of 0.10 or less is considered acceptable [203:21].

A short table of R.I. follows:

	R.I.
n=1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

Computer Programs:

Saaty [198:252-276] includes several short computer routines in various computer languages that perform the required calculations for determining the priority vectors and measure of consistency.

We used <u>Expert Choice</u> in our exercise described in Chapter Seven. A listing from <u>Expert Choice</u> is included in Appendix O. <u>Expert Choice</u> is produced by Decision Support Software, Inc., McLean, VA, for the IBM personal computer.

Appendix J: Group Decision Making with the Analytic Hierarchy Process

In Chapter Six we described how histograms of a groups' pairwise comparisons could be used to aid the decision maker in determining those areas where consensus or disagreement was predominant. Once these areas are identified the decision maker can redirect the efforts of the group to focus their dialogue on those pairwise comparisons where no consensus can be reached. Obviously, the amount of information available in the pairwise comparisons for a group problem solving session can be rather large depending on the size of the group and the size of the hierarchies used in the AHP. Automating the display of these histograms would greatly aid the efficiency of the group problem solving process.

Other types of information that can be presented to the group members to aid them in the decision making process are described below.

Members weighting of the alternative (i.e., determining the priority vector as described in Appendix I).

Smallest group weighting.

Largest group weighting.

Group average weighting.

Members consistency (as calculated from computer routine or as described in Appendix I).

Group smallest consistency.

Group largest consistency.

Group average consistency.

Besides these values above, the group's values can be weighted by each members consistency to provide a weighted group result. This gives more weighting to those who are consistent and less to those who are inconsistent. This process is described in [155:220].

The usefulness of these types of calculations must be determined by the decision maker. The focus should be on aiding the group decision making process and not on the calculation of numbers.

All of these values can be calculated and displayed using the appropriate computer software.

Appendix K: Demographic Data

The following demographic data was provided by the participants in the exercise (Chapter Seven).

Age

20–29	X X
30–39	X X
40–49	X X X X

Educational Background

Participant:	1	2	3	4	5	6	7	8
B.S.	X	X	X		X	X	X	X
M.S.			X		X			X
PhD.			X*	X				

(X* All but the dissertation has been completed)

How the participants described themselves

Participant:	1	2	3	4	5	6	7	8
Scientist	X		X					
Engineer	X	X						X
Supervisor or Manager				X				X
Technology Manager	X			X	X	X		X
Decision maker	X							X
Technology Strategist	X			X			X	X
Power Systems Analyst	X							
Program Management						X		

Self-Evaluation of the participants as to their expertise. Each participant rated himself as to how much of an expert he was in each of these technology disciplines as compared to others in these disciplines.

Autonomy

Not at all	1	X
	2	X X
	3	X X
Somewhat	4	X X
	5	X
	6	
Very Much	7	

Thermal Control

Not at all	1	X
	2	X X X
	3	X
Somewhat	4	X
	5	X X
	6	
Very Much	7	

Electro-Optics

Not at all	1	X
	2	X
	3	
Somewhat	4	X X X X
	5	X
	6	X
Very Much	7	

Information Processing

Not at all	1	X
	2	X
	3	X
Somewhat	4	X X
	5	X X
	6	X
Very Much	7	

Survivability

Not at all	1	X
	2	
	3	X X X
Somewhat	4	X X
	5	X
	6	X
Very Much	7	

Materials

Not at all	1	
	2	X X X X
	3	X
Somewhat	4	X
	5	X
	6	
Very Much	7	X

Environment

Not at all	1	
	2	X X
	3	X X
Somewhat	4	X
	5	
	6	X
Very Much	7	X X

Communications

Not at all	1	X X
	2	X
	3	
Somewhat	4	X X X X
	5	X
	6	
Very Much	7	

Manufacturing

Not at all	1	X X X
	2	X
	3	X
Somewhat	4	X X
	5	
	6	X
Very Much	7	

Test and Evaluation

Not at all	1	
	2	X X
	3	X X X
Somewhat	4	X
	5	
	6	X X
Very Much	7	

Structures

Not at all	1	X X
	2	X X
	3	X
Somewhat	4	
	5	X X
	6	
Very Much	7	X

Man-In-Space

Not at all	1	
	2	X X
	3	X X
Somewhat	4	X X
	5	X X
	6	
Very Much	7	

Radar

Not at all	1	X X
	2	X
	3	X X
Somewhat	4	X X
	5	X
	6	
Very Much	7	

Power/Energy

Not at all	1	X
	2	X
	3	X X X
Somewhat	4	
	5	X
	6	
Very Much	7	X X

Guidance/Navigation & Control

Not at all	1	X X
	2	X X
	3	
Somewhat	4	X X
	5	X X
	6	
Very Much	7	

Weapons

Not at all	1	
	2	X X
	3	X
Somewhat	4	X X X
	5	X
	6	X
Very Much	7	

Propulsion

Not at all	1	
	2	X X X
	3	X X
Somewhat	4	X
	5	X
	6	X
Very Much	7	

Appendix L: Technology Issue Assessment Exercise Instructions

Purpose and Objective of the Exercise:

Introduction:

Thank you for taking time from your busy schedules to help us in our thesis effort. We hope that your participation will also contribute to STC's continuing efforts in managing Air Force space technologies.

Purpose:

The purpose of this exercise is to obtain feedback on the proposed methodology and criteria for assessing and prioritizing space technology issues.

Objectives:

1. Determine the validity, adequacy, and usefulness of the proposed hierarchical structuring of the problem.

2. Determine the validity, adequacy, and usefulness of the proposed criteria for assessing space technology issues.

3. Determine the appropriateness of this quantitative approach for eliciting subjective judgments from space technology experts.

4. Determine if the information currently exists in order to apply the criteria in the assessment process.

Description of the Exercise:

This exercise consists of two parts. First, you will be asked to apply the criteria using the Analytic Hierarchy Process (described later) to a subset of space technology issues in your area of expertise and also to a subset of issues from a mix of disciplines.

Second, the results of this exercise will be presented to you as well as the group results. You may change your assessment at this time if the results so indicate. Once you are satisfied with the results and understand the process you will be asked to fill out a questionnaire. The questionnaire is designed to get your feedback on using the methodology.

The intent of this exercise is not to prioritize space technology issues but rather to understand and assess the proposed methodology. However, to do this you are asked to

try to apply the proposed structure and criteria to a set of space technology issues.

The results of this exercise will be used in a non-statistical assessment of the proposed methodology. Only descriptive statements of the results and the answers to the questionnaire will be used in our thesis.

Assessment Process:

Captain Chapman will explain the assessment process and present the proposed hierarchy. Please do not change the structure of the problem. We are trying to assess the methodology rather than come up with a "correct" list of prioritized technology issues.

Matrices are presented to you in order to make pairwise comparisons of time frames (technology availability dates), criteria, and space technology issues. A Scale is presented below that will be used in quantitatively describing the relative importance of items to each other.

The Analytic Hierarchy Process (AHP) is the multiple criteria decision making technique we have chosen to implement and elicit the subjective preferences of the space technology experts in the context of the criteria. On the next page is the scale to be used in the pairwise comparison of space technology issues.

Only the upper right hand portion of each matrix must be filled in. If the item in the left hand column is more important than the item across the top, then a positive number is entered from the scale. If the item in the left hand column is less important than the item across the top, then a negative number is entered from the scale. Remember, the pairwise comparisons are done in terms of which element dominates another. An example is presented below:

	A	B	C
A	1	3	-3
B		1	-6
C			1

Interpretation:

Element A is slightly more important than element B.

Element C is slightly more important than element A (note -3).

Element C is between strongly and very strongly more important than element B (again represented by -6).

Scale of Relative Importance used in the AHP

Intensity of Relative Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Slight importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above non-zero numbers	If an activity has one of the above numbers assigned to it when compared with a second activity, then the second activity has the reciprocal value when compared to the first.	

Figure L-1. AHP Scale of Relative Importance

Proposed Hierarchy:

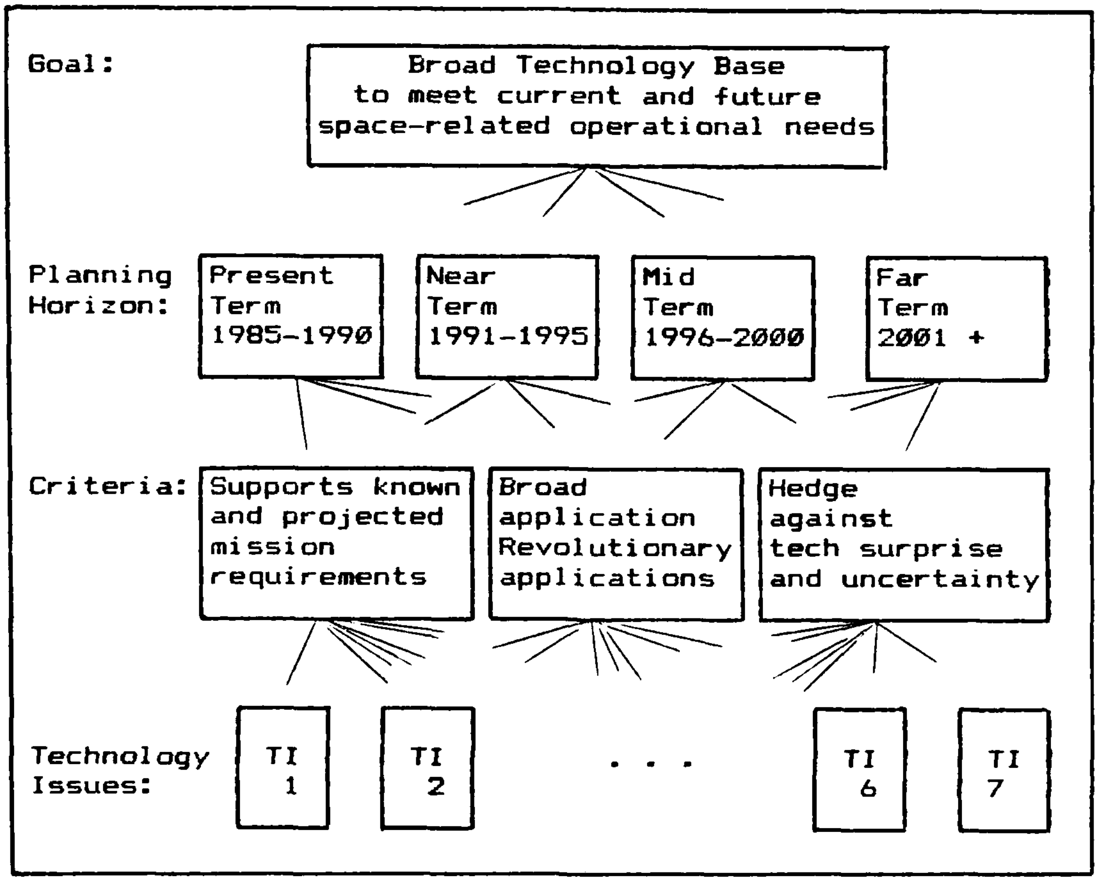

Figure L-2. AHP Hierarchy for Technology Assessment

The question to ask yourself when comparing time frames to the ultimate goal of a broad technology base responsive to operational needs: of the two (pairwise comparison) time frames being compared, which is considered more important with respect to the ultimate goal.

The question to ask yourself when comparing criteria to time frames is: of the two criteria being compared, which is considered more important in that time frame, and how much more important is one to the other.

The question to ask yourself when comparing space technology issues to each criterion is: of the two technology issues being compared, which is considered more important with respect to the criterion, and how much more important is one to the other.

Criteria for Eliciting the Subjective Preferences of Space Technology Experts

We now identify and explain the three criteria to be used in the analysis of the strategic and technical utility of various space technology issues in the context of Space Technology Advocacy.

Criterion 1: Provide performance levels necessary to meet the threat and/or projected threat within the space arena. How far does the technology issue go in supporting known or projected mission requirements and tasks?

Criterion 2: Provide alternative applications to meet many military tasks. What is the potential for exploiting the technology issue for broad applications to as yet unidentified tasks? What is the potential in the technology issue for allowing us to do current tasks in new and unexpected ways?

Criterion 3: Provide a "hedge" against technological surprise and uncertainty.

Explanation of each of the criteria follows:

Explanation of the Criteria

Criterion 1:

1. Provide performance levels necessary to meet the threat and/or projected threat within the space arena. In other words, how far does the technology issue go in supporting known mission requirements and tasks. In some cases this can be quantitatively described. The presence of a shortfall in performance level would indicate the existence of one or more technology issues. This criterion allows the decision maker to compare two technology issues in the context of how important is one to the other in terms of the quality provided by the technology issues to the successful accomplishments of military tasks. This assessment would be partly based on the application of these technology issues to various military functions and tasks and to the relative importance of these functions and tasks to each other. The relative importance of functions, tasks, and missions can be derived in several fashions.

First, mission area analysis from DoD, the Air Staff, and MAJCOM's can aid the decision maker in making the assessment. Also, policy statements from national leaders,

both civilian and military, can give the decision maker some insight into the relative importance of various missions and tasks. Other sources for this information are the planning documents that exist within DoD and the Air Force. The Space Systems Architecture study is one such document. Finally, the knowledge and experience of the decision maker is, in the end, the most important source of information and judgment for making the assessment.

Criterion 2:

2. Provide alternative applications to meet many military tasks. In other words, what is the potential for exploiting the technology issue. This is a good criterion to weight those fledgling technologies that may have application to as yet unidentified tasks and to allow us to do current tasks in new and unexpected ways. Also, this criterion can be used to weight those technology issues that can revolutionize the way we do things in space.

For example, let's take a look at laser technology. Not only does the laser have application in the future as a weapon but it also has applications in laser-gyros, laser range-finders, laser target designators, not to mention the hundreds of civilian applications of the laser. However, many of these applications could not be forecast twenty years ago. But most researchers knew there was great promise in this technology even though the applications could not be identified. In other words, a laser technology issue may be robust in the number of possible applications that can flow from it. Some of these applications may not be recognizable or have been identified until well after the maturity of the technology. However, in many cases the applications that have been identified are only the tip of the iceberg.

Criterion 3:

3. Provide a "hedge" against technological surprise and uncertainty. In the space technology advocacy problem the fact that a program or technology issue is high risk and/or uncertain may be a good reason to go ahead and budget for it in order to reduce the uncertainty. Sometimes the high risk/high payoff technology is the one to pursue in terms of satisfying future, and possibly unidentified, mission requirements. For example, some of the SDI technology issues are important to investigate because their resolution will determine the very feasibility of the concept of Ballistic Missile Defense (BMD). Determining this feasibility will have a major impact on future defense options and will definitely have a tremendous impact on the national budget.

This criterion is also important in the sense that it helps identify those areas of research that are worth doing just for the sake of reducing uncertainty. Finally, if potential adversaries are involved in certain technology areas we may be obliged to undertake equivalent research in order to hedge against a potential technology disadvantage.

Summary: From this description it becomes readily apparent that these three criteria are extremely difficult if not impossible to measure quantitatively. Whether or not a technology issue contributes more or less to these criteria is a subjective appraisal. However, this exercise and your feedback will help us determine the validity of using these criteria in eliciting subjective preferences and judgments from space technology experts.

Appendix M: Exercise Interview Schedule (Questionnaire)

Interview Schedule

Now that you have made the space technology assessments, we would like your opinion on a number of questions.

Instructions

The questions should take no more than 15 minutes of your time to answer.

The opinions you express will be used to evaluate the methodology we have proposed for space technology advocacy in our thesis effort.

None of the questions require you, nor are they intended for you, to look up data or other information.

We suggest that you answer the questions quickly after reading them carefully. Only your reactions are sought.

If you should wish to amplify a question or to ask a question about an item, please feel free to do so.

We will apply the principle of non-attribution. The identity of individuals responding to our questionnaire will not be revealed. Your name will not be associated with any information you provide. Strict anonymity will be maintained throughout the study.

Job Title ______________________________

Age __ 20-29 __30-39 __40-49 __50+

Educational Background (multiple answers are OK)

B.S. __ Major field ______________________
M.S. __ ______________________
PhD. __ ______________________
Other (specify) __ ______________________

In which of the following space technology disciplines do you consider yourself an expert or specialist? Please circle the scale to indicate the extent to which you think of yourself as a specialist or expert (relative to others in your field)

Autonomy

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Thermal Control

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Electro-Optics

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Information Processing

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Survivability

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Materials

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Environment

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Communications

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Manufacturing

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Test and Evaluation

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Structures

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Man-In-Space

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Radar

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Power/Energy

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Guidance/Navigation & Control

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Weapons

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Propulsion

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Other (specify) ______________________________

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Would you describe yourself primarily as (more than one answer is OK) (Check the appropriate items).

Scientist	__
Engineer	__
Supervisor or Manager	__
Technology Manager	__
Decision maker	__
Technology Strategist	__
Other (specify)	__ ____________________

Were you familiar with the Analytic Hierarchy Process (prior to this). Indicate the level of familiarity on the following scale.

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Have you ever used the Analytic Hierarchy Process as an aid for selecting or assessing possible alternatives (in any aspect of your job or profession)?

Not at all			Somewhat			Very much
1	2	3	4	5	6	7

Do you currently use any formalized method or technique for assessing or prioritizing technology issues?

Yes __
No __

For the following questions, circle the number which best indicates your evaluation of each statement.

I understood what I was required to do for this exercise in assessing the space technology issues.

1	2	3	4	5
not at all clear	not very clear	somewhat clear	fairly clear	very clear

I am now using or have used quantitative analytical methods in my work for setting priorities.

1	2	3	4	5
much too little	too little	about right	too much	much too much

The description of Criterion 1 made sense to me.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The description of Criterion 2 made sense to me.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The description of Criterion 3 made sense to me.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The Hierarchy is appropriate for this type of analysis.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I was able to apply Criterion 1 in the pairwise comparison of space technology issues.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I was able to apply Criterion 2 in the pairwise comparison of space technology issues.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I was able to apply Criterion 3 in the pairwise comparison of space technology issues.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The results of the assessment are close to how I would rank order the space technology issues in order of importance.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The three criteria represent a good way to evaluate the potential military strategic and technical utility of space technology issues.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I would consider using this approach in the future in a formalized manner to assess technology issues.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I feel qualified to use these three criteria in assessing space technology issues.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I feel qualified to assess technology issues in terms of military doctrine.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The information available to me about the space technology issues is adequate for this type of assessment in the context of criterion 1.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The information available to me about the space technology issues is adequate for this type of assessment in the context of criterion 2.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The information available to me about the space technology issues is adequate for this type of assessment in the context of criterion 3.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

Of the three criteria, which one was easiest to apply?

Criteria 1 __
Criteria 2 __
Criteria 3 __

Of the three criteria, which one was most difficult to apply?

Criteria 1 __
Criteria 2 __
Criteria 3 __

<u>The next four statements are closely related so please read carefully.</u>

The ultimate goal for resolving space technology issues is to provide a broad technology base to meet current and future operational needs.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The ultimate goal for resolving space technology issues is to provide a broad technology base that is responsive to operational needs.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The ultimate goal for resolving space technology issues is to provide a broad technology base that is responsive to operational needs currently known, projected, or as yet unidentified.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The ultimate goal for resolving space technology issues is to build space systems.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I feel that decisions made by using this system would more closely reflect the attitudes and beliefs of the decision maker than if I did not use the system and arbitrarily developed a scoring model.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The results using this approach are the same that I would obtain if I did not use this approach.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The results using this approach would be valuable in setting priorities for budgetary decisions for space R&D technology programs.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The overall quality of my decisions would be increased by using this methodology because of the formalized structure of the problem and the criteria used.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

This method requires too much time and effort to compare and prioritize space technology issues.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The measure of my consistency in setting space technology issue priorities is an important element in using this approach.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

Consistency is important to me when making decisions.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The information required for this type of analysis does not currently exist.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

The manner in which technology issues are currently assessed is adequate and should not be changed.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

Technology issues need to be assessed and prioritized in the context of the three criteria.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I feel qualified to assess technology issues outside my area(s) of expertise.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

I feel qualified to assess technology issues outside my area of expertise in terms of the three criteria.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

After participating in this exercise I would adopt this methodology and the criteria whenever I must make an assessment of a set of space technology issues.

1	2	3	4	5
strongly disagree	disagree	not sure	agree	strongly agree

Appendix N: Listing of Space Technology Issues Used in the Space Technology Assessment Exercise

The following four sets of space technology issues were used in the exercise to elicit the subjective preferences of space technology experts. The first set of issues were taken from the space power/energy technology discipline. The second set are space materials issues. The other two sets of issues reflect a mixture of issues from various space technology disciplines. All participants assessed at least one of the sets below.

Space Power/Energy Issues

Electrochemical Energy Storage
Advanced Survivable Solar Array
100 Kilowatt Nuclear Reactor
Solar Thermal Dynamic Power System
Multimegawatt Nuclear Reactor
Dynamic Isotope Power System
Nonnuclear Prime Power

Space Materials Issues

Metal Matrix Composites
Organic Matrix Composites
Vibration Damping Materials
Adhesives, Seals, and Sealants
Space Lubricants
Printed Wiring Board Substrates
Electrical Insulation Materials

First Mixed Set of Issues

Laser Cross Links
Ionospheric Propagation
Data Processing
Optics Production
IR Focal Plane
Deployable/Erectable Structures
Autonomous Satellite Maintenance

Second Mixed Set of Issues

- Laser Survivability
- Manned Performance Enhancement
- Metal Matrix Composites
- Orbital Transfer Vehicle Propulsion Performance
- EHF Nulling Antenna
- Cryogenic Refrigerators
- Autonomous Navigation

Appendix O: Listing of Printout From Expert Choice

The following listing is the output from the commercially available AHP software called Expert Choice. This listing shows how the space technology advocate might evaluate the set of materials issues listed in Appendix N. The following abbreviations were used:

Metal Matrix Composites	METMATRX
Organic Matrix Composites	ORMATRXC
Vibration Damping Materials	ViBDAMP
Adhesives, Seals, and Sealants	ADSEALS
Space Lubricants	LUBRICNT
Printed Wiring Board Substrates	WRNGSUBS
Electrical Insulation Materials	ELINSULA

Each section of the listing identifies the level of the hierarchy being evaluated with respect to the next higher level. Following this is the upper half of the matrix of pairwise comparisons. Negative values (actually the reciprocal value) are identified by parenthesis. Following the matrix is the weighted priority vector along with a histogram show the relative weightings. The inconsistency ratio is then presented. Finally, an overall tally of the evaluation is listed followed by the overall priority vector and the accompanying histogram.

```
                    JUDGMENTS WITH RESPECT TO
                         GOAL  OF BROAD TECHNOLOGY BASE

                        A     B     C     D
         A: PRESTERM          5.0   9.0   9.0
         B: NEARTERM                9.0   9.0
         C: MIDTERM                       9.0
         D: FARTERM

   1 EQUAL    3 MODERATE    5 STRONG    7 VERY STRONG    9 EXTREME

0.605
PRESTERM XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.283
NEARTERM XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.085
MIDTERM  XXXXXXXXXX

0.027
FARTERM  XXX

                       INCONSISTENCY RATIO = 0.372



                    JUDGMENTS WITH RESPECT TO
                                  PRESTERM

                        A     B     C
         A: CRIT1             5.0   7.0
         B: CRIT2                   3.0
         C: CRIT3

   1 EQUAL    3 MODERATE    5 STRONG    7 VERY STRONG    9 EXTREME

0.731
CRIT1    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.188
CRIT2    XXXXXXXXXXXXXXXXXX

0.081
CRIT3    XXXXXXXX

                       INCONSISTENCY RATIO = 0.056
```

```
                    JUDGMENTS WITH RESPECT TO
                               NEARTERM

                     A     B     C
       A: CRIT1           3.Ø   5.Ø
       B: CRIT2                 5.Ø
       C: CRIT3

  1 EQUAL     3 MODERATE     5 STRONG     7 VERY STRONG     9 EXTREME

Ø.618
CRIT1     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Ø.297
CRIT2     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Ø.Ø86
CRIT3     XXXXXXXXXX

                    INCONSISTENCY RATIO = Ø.117


                    JUDGMENTS WITH RESPECT TO
                               MIDTERM

                     A     B     C
       A: CRIT1         (3.Ø) (3.Ø)
       B: CRIT2                 1.Ø
       C: CRIT3

  1 EQUAL     3 MODERATE     5 STRONG     7 VERY STRONG     9 EXTREME

Ø.143
CRIT1     XXXXXXXXXXXXXXXXXXXXXXX

Ø.429
CRIT2     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Ø.429
CRIT3     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

                    INCONSISTENCY RATIO = Ø.ØØØ
```

JUDGMENTS WITH RESFECT TO
FARTERM

	A	B	C
A: CRIT1		(5.0)	(5.0)
B: CRIT2			1.0
C: CRIT3			

1 EQUAL 3 MODERATE 5 STRONG 7 VERY STRONG 9 EXTREME

0.091
CRIT1 XXXXXXXXXXXXXX

0.455
CRIT2 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.455
CRIT3 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.000

JUDGMENTS WITH RESFECT TO
CRIT1

	A	B	C	D	E	F	G
A: METMATRX		5.0	3.0	7.0	5.0	5.0	5.0
B: ORMATRXC			(5.0)	3.0	(5.0)	1.0	(3.0)
C: VIBDAMP				5.0	3.0	5.0	3.0
D: ADSEALS					(5.0)	1.0	(3.0)
E: LUBRICNT						5.0	3.0
F: WRNGSUBS							(3.0)
G: ELINSULA							

1 EQUAL 3 MODERATE 5 STRONG 7 VERY STRONG 9 EXTREME

0.398
METMATRX XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.050
ORMATRXC XXXXXXXXX

0.229
VIBDAMP XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.034
ADSEALS XXXXXX

0.159
LUBRICNT XXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.041
WRNGSUBS XXXXXXX

0.089
ELINSULA XXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.073

JUDGMENTS WITH RESPECT TO
CRIT2

	A	B	C	D	E	F	G
A: METMATRX		7.0	3.0	7.0	3.0	5.0	5.0
B: ORMATRXC			(5.0)	1.0	(5.0)	3.0	(3.0)
C: VIBDAMP				7.0	3.0	5.0	3.0
D: ADSEALS					(5.0)	1.0	(3.0)
E: LUBRICNT						5.0	(3.0)
F: WRNGSUBS							(5.0)
G: ELINSULA							

1 EQUAL 3 MODERATE 5 STRONG 7 VERY STRONG 9 EXTREME

0.380
METMATRX XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.047
ORMATRXC XXXXXXXXX

0.237
VIBDAMP XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.036
ADSEALS XXXXXXX

0.125
LUBRICNT XXXXXXXXXXXXXXXXXXXXXXXX

0.034
WRNGSUBS XXXXXX

0.142
ELINSULA XXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.087

JUDGMENTS WITH RESPECT TO
CRIT3

	A	B	C	D	E	F	G
A: METMATRX		5.0	3.0	5.0	3.0	7.0	3.0
B: ORMATRXC			(5.0)	1.0	(5.0)	1.0	(5.0)
C: VIBDAMP				5.0	3.0	7.0	3.0
D: ADSEALS					(5.0)	3.0	(3.0)
E: LUBRICNT						5.0	3.0
F: WRNGSUBS							(5.0)
G: ELINSULA							

1 EQUAL 3 MODERATE 5 STRONG 7 VERY STRONG 9 EXTREME

0.345
METMATRX XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXY(XXXXXXXXXXXXXXXXXX

0.039
ORMATRXC XXXXXXXX

0.249
VIBDAMP XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.049
ADSEALS XXXXXXXXXX

0.173
LUBRICNT XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.030
WRNGSUBS XXXXXX

0.114
ELINSULA XXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.069

BROAD TECHNOLOGY BASE
TALLY FOR LEVEL 3 NODES

```
LEVEL 1          LEVEL 2           LEVEL 3           LEVEL 4          LEVEL 5
-------          -------           -------           -------          -------

PRESTERM =  605
.                CRIT1     =  442
.                .                 METMATRX =  176
.                .                 VIBDAMP  =  101
.                .                 LUBRICNT =   70
.                .                 ELINSULA =   39
.                .                 ORMATRXC =   22
.                .                 WRNGSUBS =   18
.                .                 ADSEALS  =   15
.                CRIT2     =  114
.                .                 METMATRX =   43
.                .                 VIBDAMP  =   27
.                .                 ELINSULA =   16
.                .                 LUBRICNT =   14
.                .                 ORMATRXC =    5
.                .                 ADSEALS  =    4
.                .                 WRNGSUBS =    4
.                CRIT3     =   49
.                .                 METMATRX =   17
.                .                 VIBDAMP  =   12
.                .                 LUBRICNT =    8
.                .                 ELINSULA =    6
.                .                 ADSEALS  =    2
.                .                 ORMATRXC =    2
.                .                 WRNGSUBS =    1
NEARTERM =  283
.                CRIT1     =  174
.                .                 METMATRX =   70
.                .                 VIBDAMP  =   40
.                .                 LUBRICNT =   28
.                .                 ELINSULA =   15
.                .                 ORMATRXC =    9
.                .                 WRNGSUBS =    7
.                .                 ADSEALS  =    6
.                CRIT2     =   84
.                .                 METMATRX =   32
.                .                 VIBDAMP  =   20
.                .                 ELINSULA =   12
.                .                 LUBRICNT =   10
.                .                 ORMATRXC =    4
.                .                 ADSEALS  =    3
.                .                 WRNGSUBS =    3
.                CRIT3     =   24
.                .                 METMATRX =    8
.                .                 VIBDAMP  =    6
.                .                 LUBRICNT =    4
.                .                 ELINSULA =    3
.                .                 ADSEALS  =    1
.                .                 ORMATRXC =    1
.                .                 WRNGSUBS =    1
MIDTERM  =   85
.                CRIT2     =   37
```

BROAD TECHNOLOGY BASE
TALLY FOR LEVEL 3 NODES

```
LEVEL 1          LEVEL 2          LEVEL 3             LEVEL 4          LEVEL 5
-------          -------          -------             -------          -------

   .                .             METMATRX =   14
   .                .             VIBDAMP  =    9
   .                .             ELINSULA =    5
   .                .             LUBRICNT =    5
   .                .             ORMATRXC =    2
   .                .             ADSEALS  =    1
   .                .             WRNGSUBS =    1
   .             CRIT3     =   37
   .                .             METMATRX =   13
   .                .             VIBDAMP  =    9
   .                .             LUBRICNT =    6
   .                .             ELINSULA =    4
   .                .             ADSEALS  =    2
   .                .             ORMATRXC =    1
   .                .             WRNGSUBS =    1
   .             CRIT1     =   12
   .                .             METMATRX =    5
   .                .             VIBDAMP  =    3
   .                .             LUBRICNT =    2
   .                .             ELINSULA =    1
   .                .             ORMATRXC =    1
   .                .             WRNGSUBS =    1
   .                .             ADSEALS  =    Ø
FARTERM  =   27
   .             CRIT2     =   12
   .                .             METMATRX =    5
   .                .             VIBDAMP  =    3
   .                .             ELINSULA =    2
   .                .             LUBRICNT =    2
   .                .             ORMATRXC =    1
   .                .             ADSEALS  =    Ø
   .                .             WRNGSUBS =    Ø
   .             CRIT3     =   12
   .                .             METMATRX =    4
   .                .             VIBDAMP  =    3
   .                .             LUBRICNT =    2
   .                .             ELINSULA =    1
   .                .             ADSEALS  =    1
   .                .             ORMATRXC =    Ø
   .                .             WRNGSUBS =    Ø
   .             CRIT1     =    2
   .                .             METMATRX =    1
   .                .             VIBDAMP  =    1
   .                .             LUBRICNT =    Ø
   .                .             ELINSULA =    Ø
   .                .             ORMATRXC =    Ø
   .                .             WRNGSUBS =    Ø
   .                .             ADSEALS  =    Ø
```

BROAD TECHNOLOGY BASE

LEVEL 3 NODES SORTED BY PRIORITY

```
METMATRX Ø.387 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
VIBDAMP  Ø.233 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
LUBRICNT Ø.153 XXXXXXXXXXXXXXXXXXXXXXXXX
ELINSULA Ø.1Ø5 XXXXXXXXXXXXXXXXX
ORMATRXC Ø.Ø48 XXXXXXXX
WRNGSUBS Ø.Ø38 XXXXXX
ADSEALS  Ø.Ø36 XXXXXX
               =====
               1.ØØØ
```

LEVEL 3 NODES SORTED BY NAME

```
ADSEALS  Ø.Ø36 XXXXXX
ELINSULA Ø.1Ø5 XXXXXXXXXXXXXXXXX
LUBRICNT Ø.153 XXXXXXXXXXXXXXXXXXXXXXXXX
METMATRX Ø.387 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
ORMATRXC Ø.Ø48 XXXXXXXX
VIBDAMP  Ø.233 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
WRNGSUBS Ø.Ø38 XXXXXX
               =====
               1.ØØØ
```

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